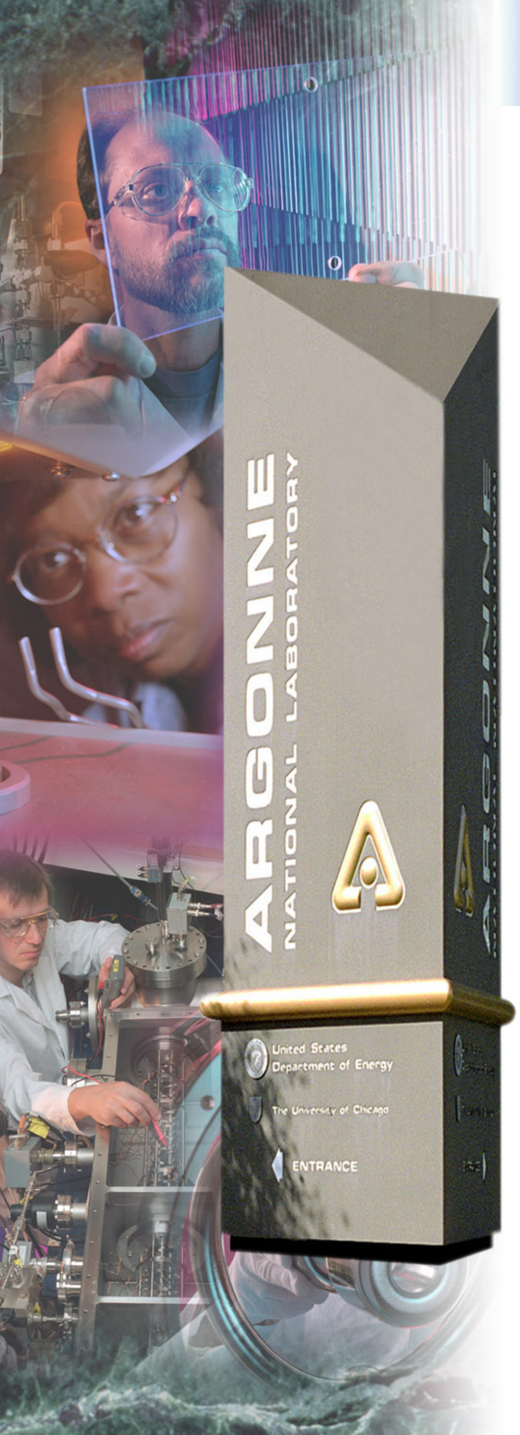

ARGONNE NATIONAL LABORATORY

Advanced Laser Ignition System (ALIS) Integrated ARICE System for Distributed Generation in California

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<u>Sponsors</u>
CEC-ARICE — *Dr. Avtar Bining*
USDOE-DE — *Ronald Fiskum*

THE UNIVERSITY OF CHICAGO

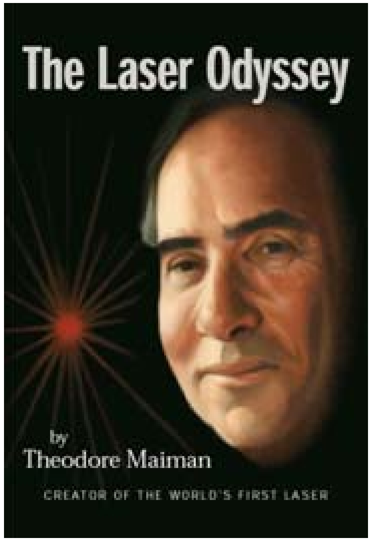
Argonne National Laboratory is managed by The University of Chicago for the U.S. Department of Energy

ALIS Critical Project Review
November 8th, 2005

When was the Laser Invented?

- Charles Townes
- Nobel Laureate
- Invented Maser 1951
- Theorized the concept and filed for laser patent 1958

- Gordon Gould
- Perennial Graduate student
- Conceptualized and built first Laser 1958
- Filed for laser patent late 1959



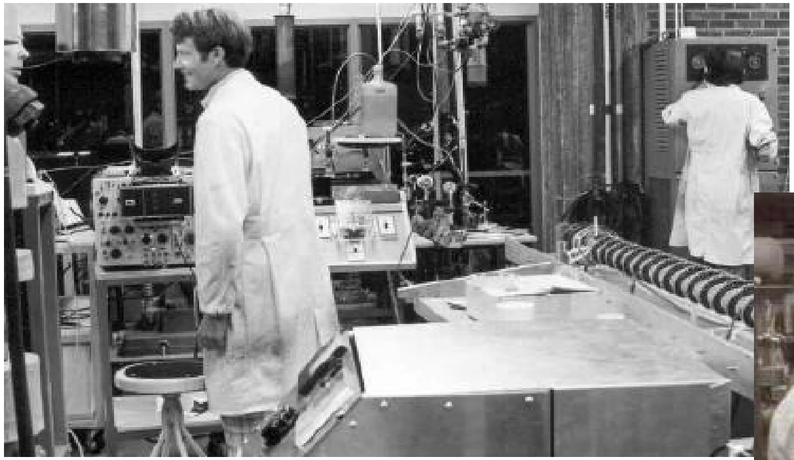
- Theodore Maiman
- Built the first Ruby Laser, 1961
- LA man's light ray outshine's sun…Horror weapon looms

Circa. 1964

- Use of lasers for ignition was demonstrated

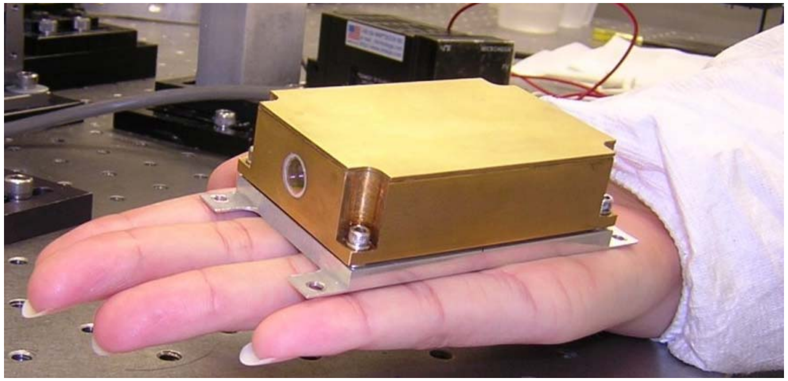
Circa. 1975

- Prof. Douglas Dale, University of Calgary, Alberta, used a 14 ft. CO_2 laser for ignition in an IC engine



By Year 2000

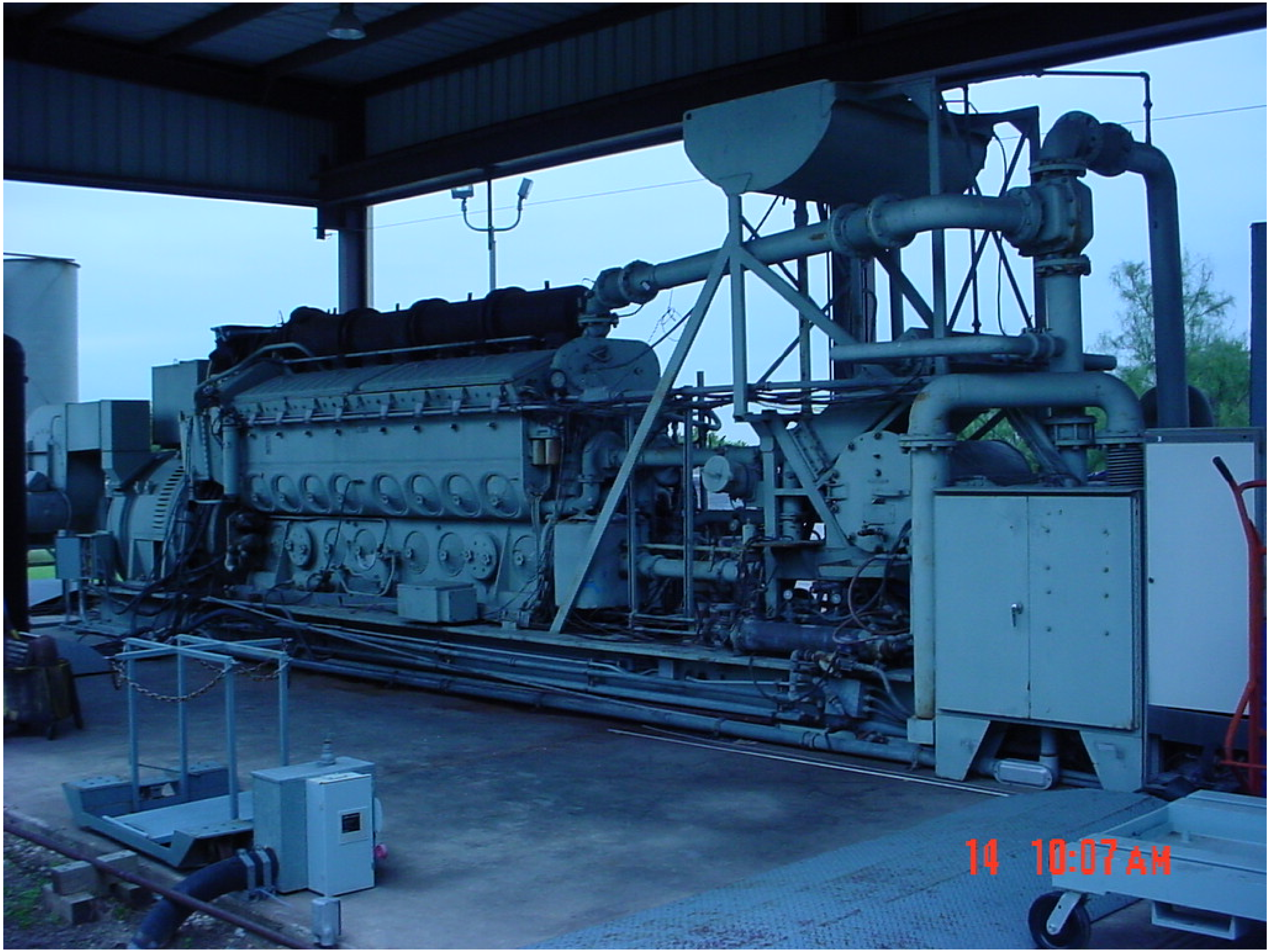
- Lasers have shrunk in size



- Rapid advancements in fiber optics
- Substantial decrease in cost of electro-optics

Revisit laser ignition

Natural gas Fired Reciprocating Engines, 0.5 – 20 MW, are Used for Power Generation and Pumping Applications



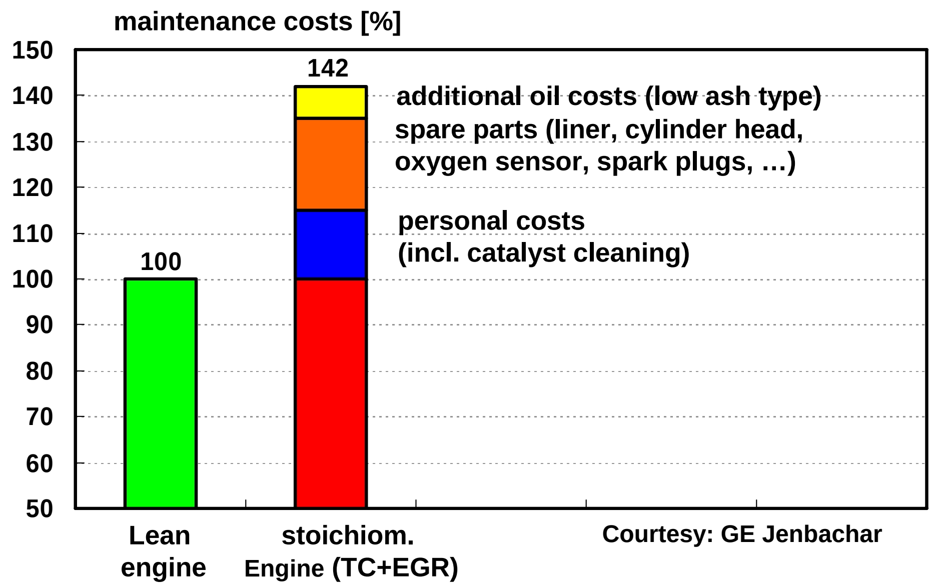
Performance Targets for
Advanced Reciprocating Internal Combustion Engines (ARICE)

Parameter	2003	2005	2007	2010
Efficiency				
Brake Thermal Efficiency	>40%	>42%	>45%	>50%
Fuel-to-Electric Efficiency*	>38%	>40%	>43%	>50%
Overall Efficiency (CHP)	>85%	>85%	>86%	>88%
Emissions – *shaft power (g/bhp-hr)*				
Oxides of Nitrogen (NOx)	<0.15	<0.15	<0.015	≈0.01
Carbon Monoxide (CO)	<1.77	<1.77	<0.02	<0.02
Volatile Organic Compounds (VOCs)	<0.3	<0.3	<0.006	<0.006
Particulate Matter (PM10)	<0.01	<0.01	<0.01	<0.01
Emissions – *power generation (lb/MW$_e$hr)*				
Oxides of Nitrogen (NOx)	<0.5	<0.5	<0.05	≈0.03
Carbon Monoxide (CO)	<6.0	<6.0	<0.08	<0.08
Volatile Organic Compounds (VOCs)	<1.0	<1.0	<0.02	<0.02
Particulate Matter (PM10)	<0.03	<0.03	<0.03	<0.03
Cost				
Complete Installed Cost ($/kW$_e$)	<800	<750	<700	<600
O&M Cost ($/kW$_e$h)	<0.006	<0.005	<0.005	<0.004
Availability & Durability				
Availability	>88%	>90%	>92%	>95%
B10 Durability (hours)	>8,000	>9,000	>10,000	>12,000
Mean Time Between Major Overhaul (hours)	>35,000	>40,000	>45,000	>50,000

Three Main Approaches to Attain NO_x Control Through Low-Temperature Combustion

- Lean-burn ($\phi < 1$) & Turbo-charged

- Rich-burn ($\phi = 1$) with Exhaust Gas Recirculation (EGR) and 3-way catalyst



Issues: High-maintenance costs, low efficiencies

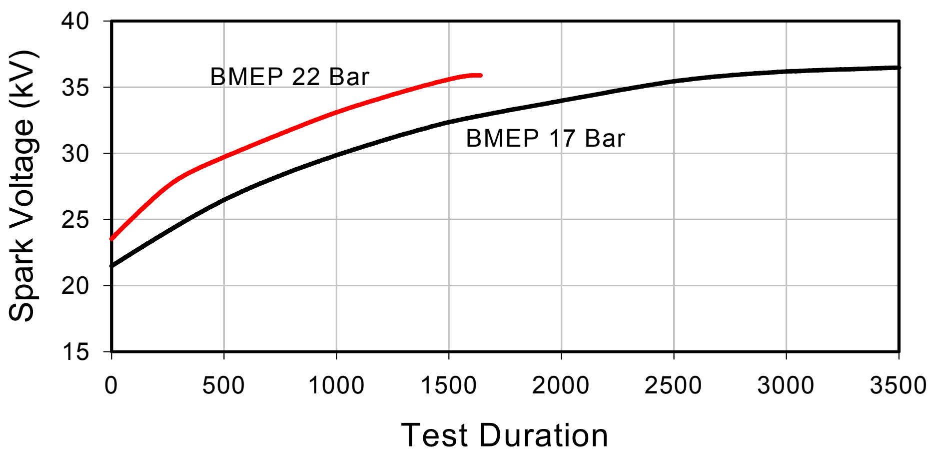
- Homogenous Charge Compression Ignition (HCCI)

Issues: startability, power density, control

The Ignition Problem in Natural Gas Engines:
Spark Plug Voltage and Spark Plug Durability

Lean operation ($\phi < 0.65$)
High boost pressures
High BMEP levels

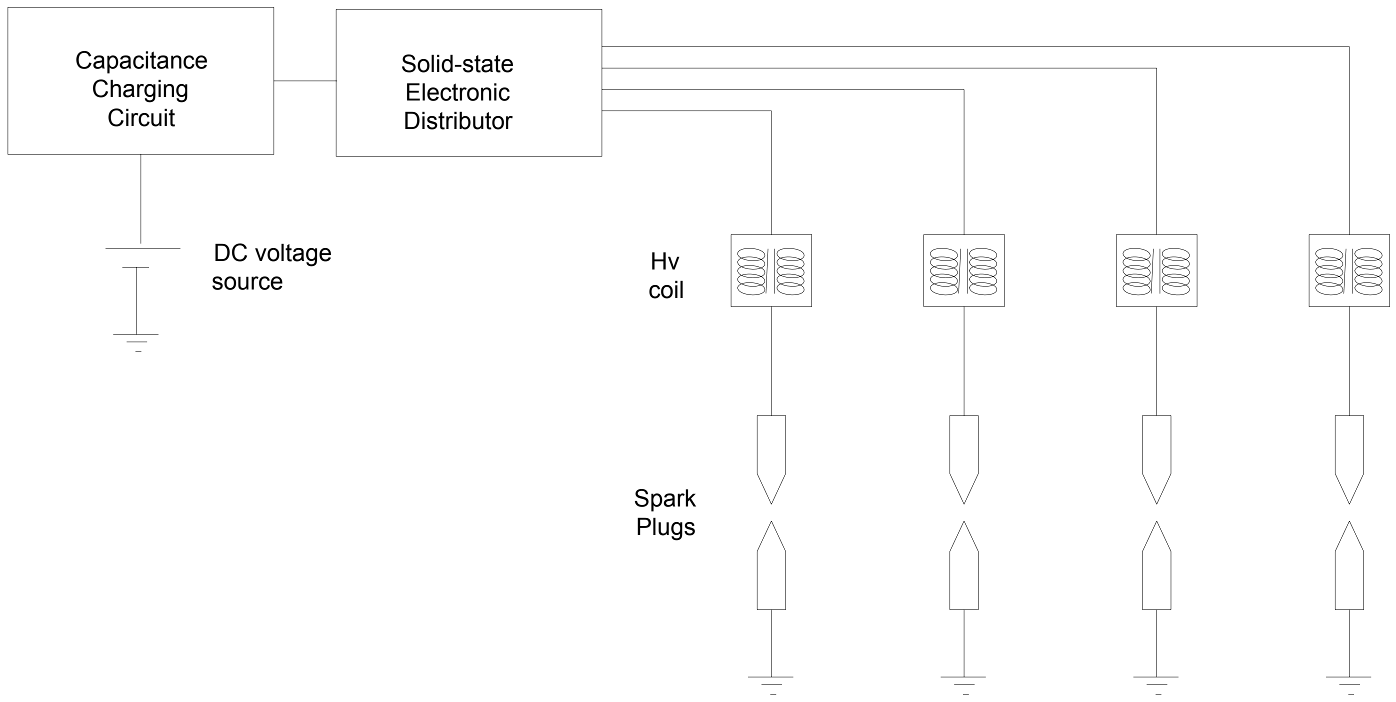
High in-cylinder densities that require ignition voltages > 40 kV



Kopecek et al.,
ASME ICE-Vol. 35-2, 2000

- Spark plug durability compromised for BMEP > 18 Bar
  - (AVL, ASME ICES2005-1094)
- Desirable spark gap adjustment interval > 8000 Hrs

Though Very Advanced, Capacitance Discharge Ignition (CDI) Cannot Meet the Present Requirements

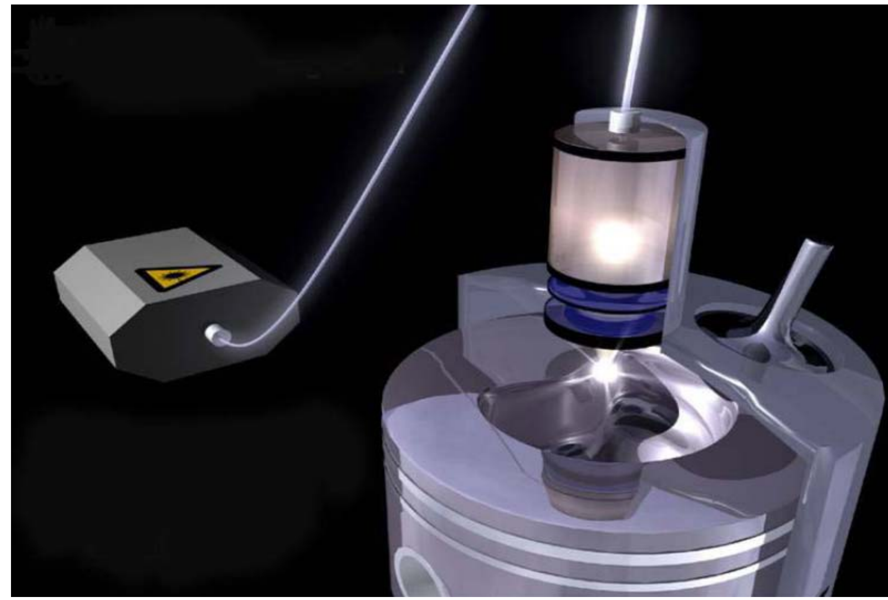


- 100 – 125 mJ/strike
- < 32 kV

Advantages of Laser Based Ignition

- **Ignition of mixtures at higher pressures**
  - *Higher BMEPs*
  - *Higher engine efficiencies*
- **Ignition of leaner mixtures**
  - *Lower NO_x emissions*
- **Ignition of Lower Quality Fuels**
  - *Syn gas, sewer gas, landfill gas, (CO_2: 20-50%)*
- **Lower maintenance requirements**
  - *Maintenance of spark gap not required*

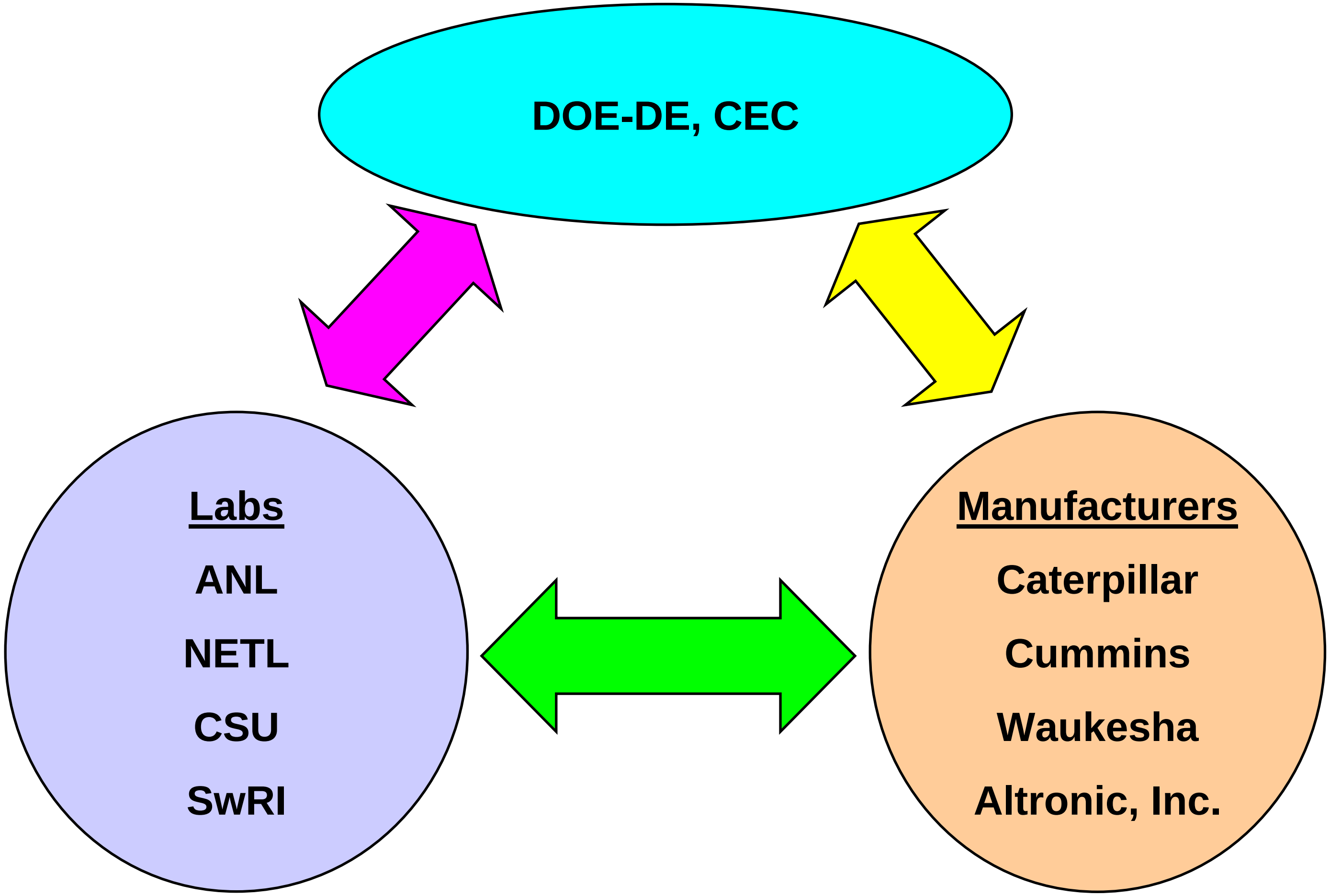
Overseas Laser Ignition Efforts



GE-Jenbacher

- Mitsubishi Heavy Industries
- Toyota – Denso Consortium

Advanced Laser Ignition System (ALIS) Consortium was Formed in 2002



- Very successful.
- Serves as a role model for other DOE-DE programs

Technical Tasks

Task	Task Name
2.1	Program coordination
2.2	Experimental Studies to determine design specifications
2.3	Development of ALIS hardware
2.4	Laser ignition tests in a single-cylinder engine
2.5	Integrate ALIS for performance on a multi-cylinder engine
2.6	Performance Evaluation of ALIS-ARICE system
2.7	Economic Evaluation for feasibility
	Final report

Task 2.1 Program Coordination

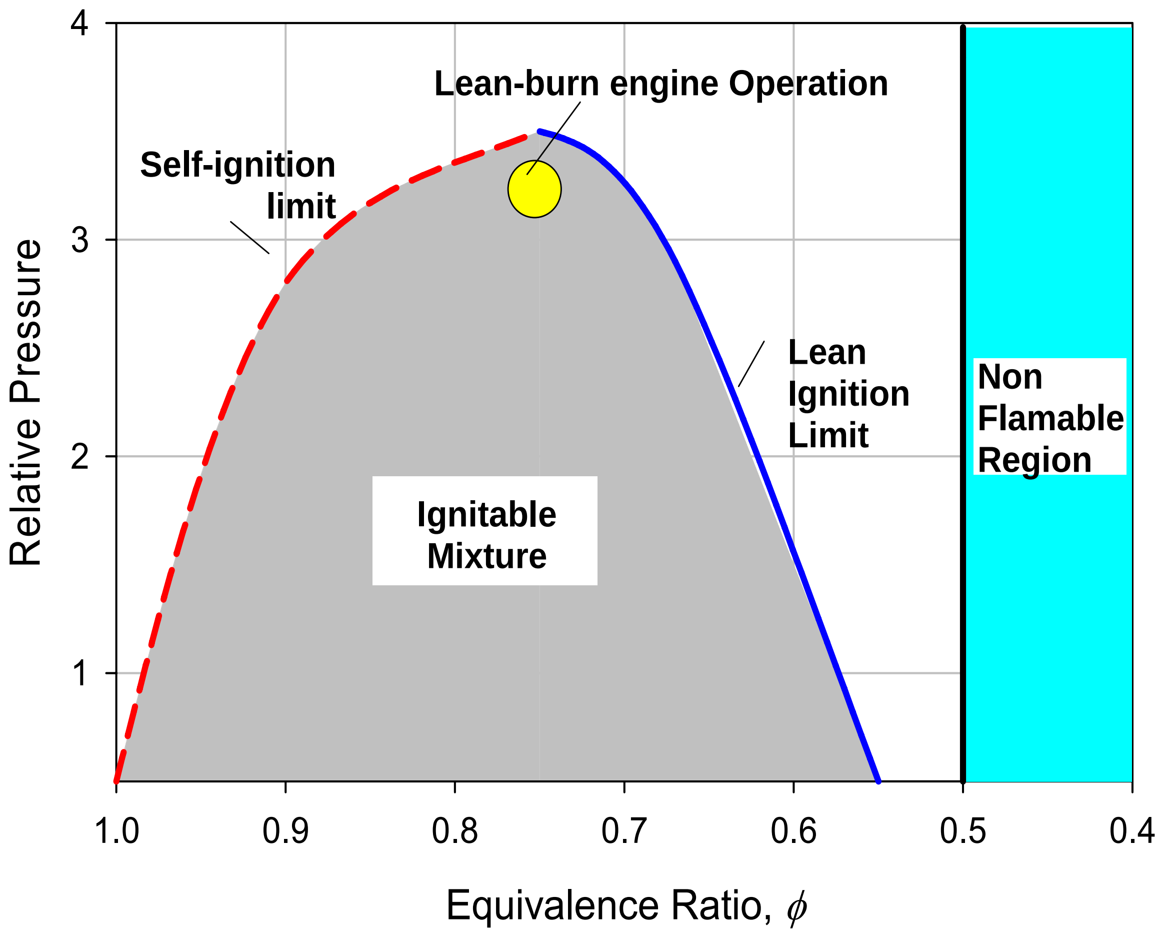
- Twenty one monthly conference calls
- Twenty one monthly progress reports
- Numerous meetings
  - *Argonne, IL*
  - *Diamond Bar, CA*
  - *Fort Collins, CO*

Task 2.2
Experimental Studies to Determine Design Specifications

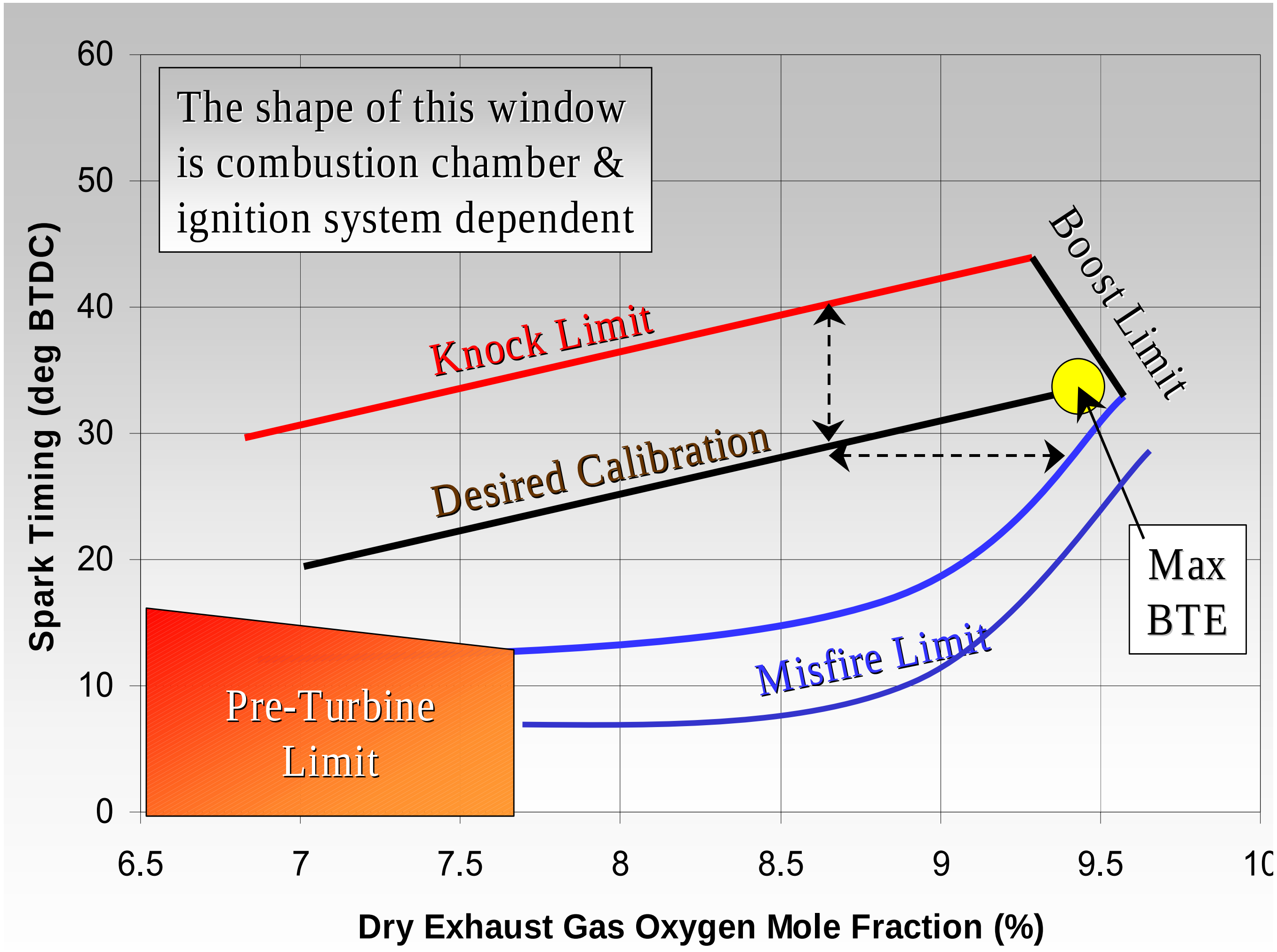
Objective

- To perform fundamental studies to characterize laser based ignition of natural gas - air mixtures.
- Natural Gas Composition: Pipeline at ANL
  - *Laser Ignition vs. Conventional Ignition*
  - *Extension of the boundaries of operation*
    - *Pressure*
    - *Equivalence ratio*
    - *Temperature*
  - *Quantify various influences*
    - *Laser energy*
    - *Focal length*
    - *Beam quality*

To Maximize the Benefits, Lean-burn Engines are Operated at the Intersection of Ignition Boundaries



High η and Low Emissions are Achieved by Operating Engines Near Point of Intersection

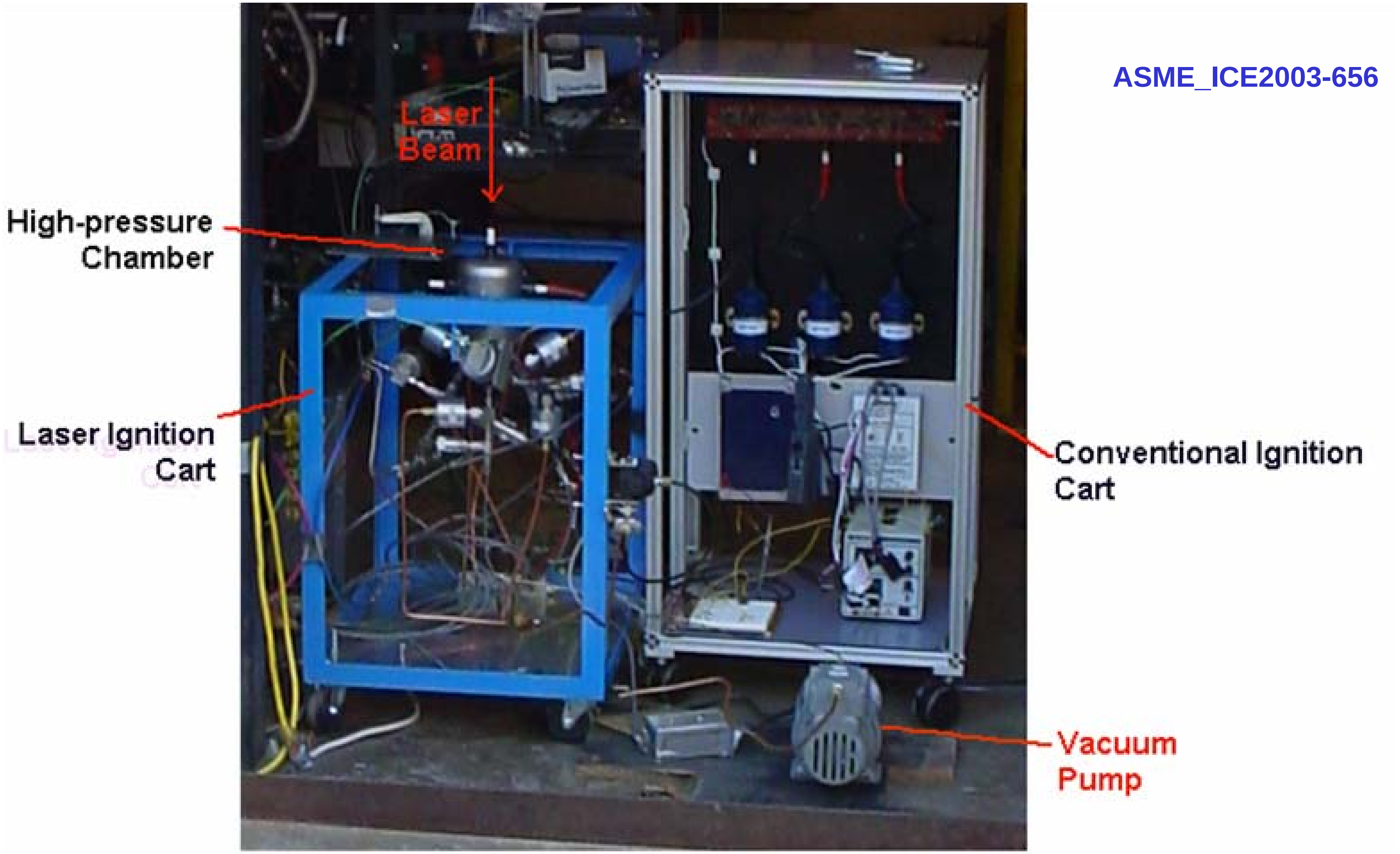


Courtesy:

SwRI

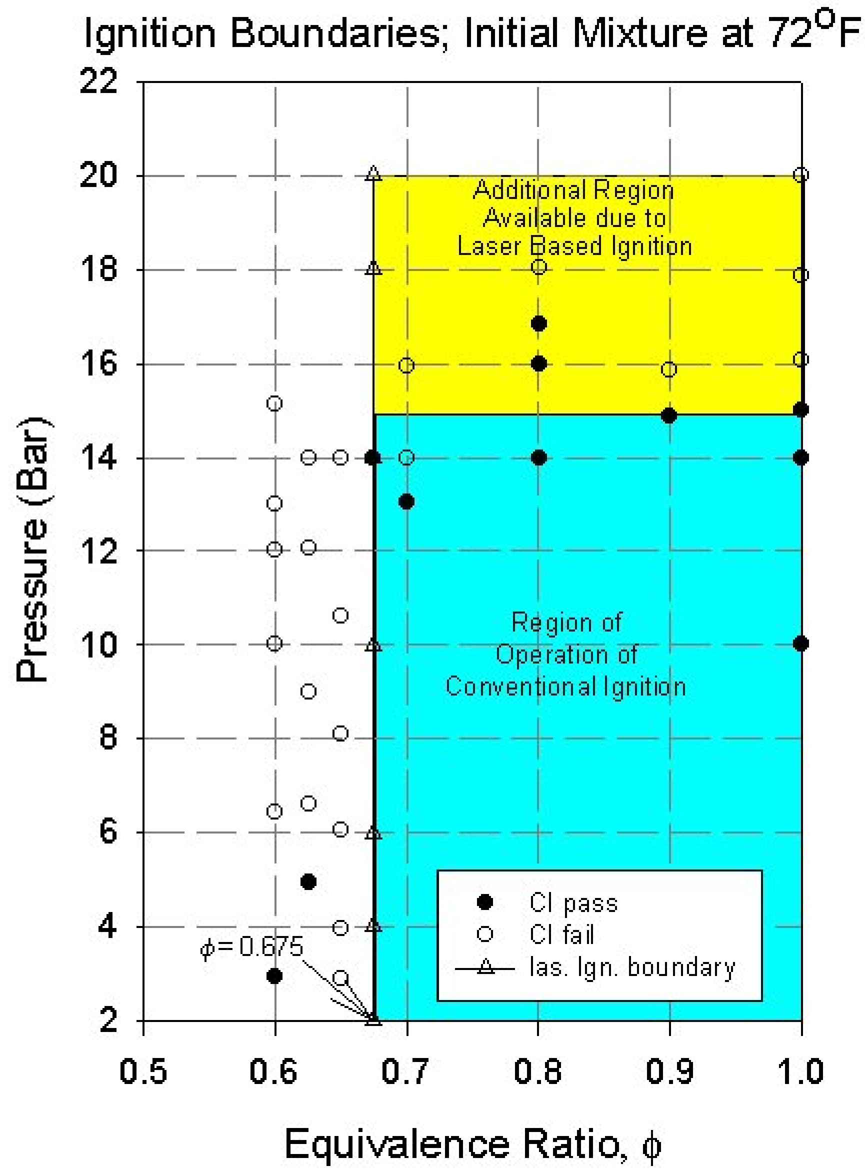
Initially A Static Chamber was Used to Determine Laser Ignition Characteristics

ASME_ICE2003-656

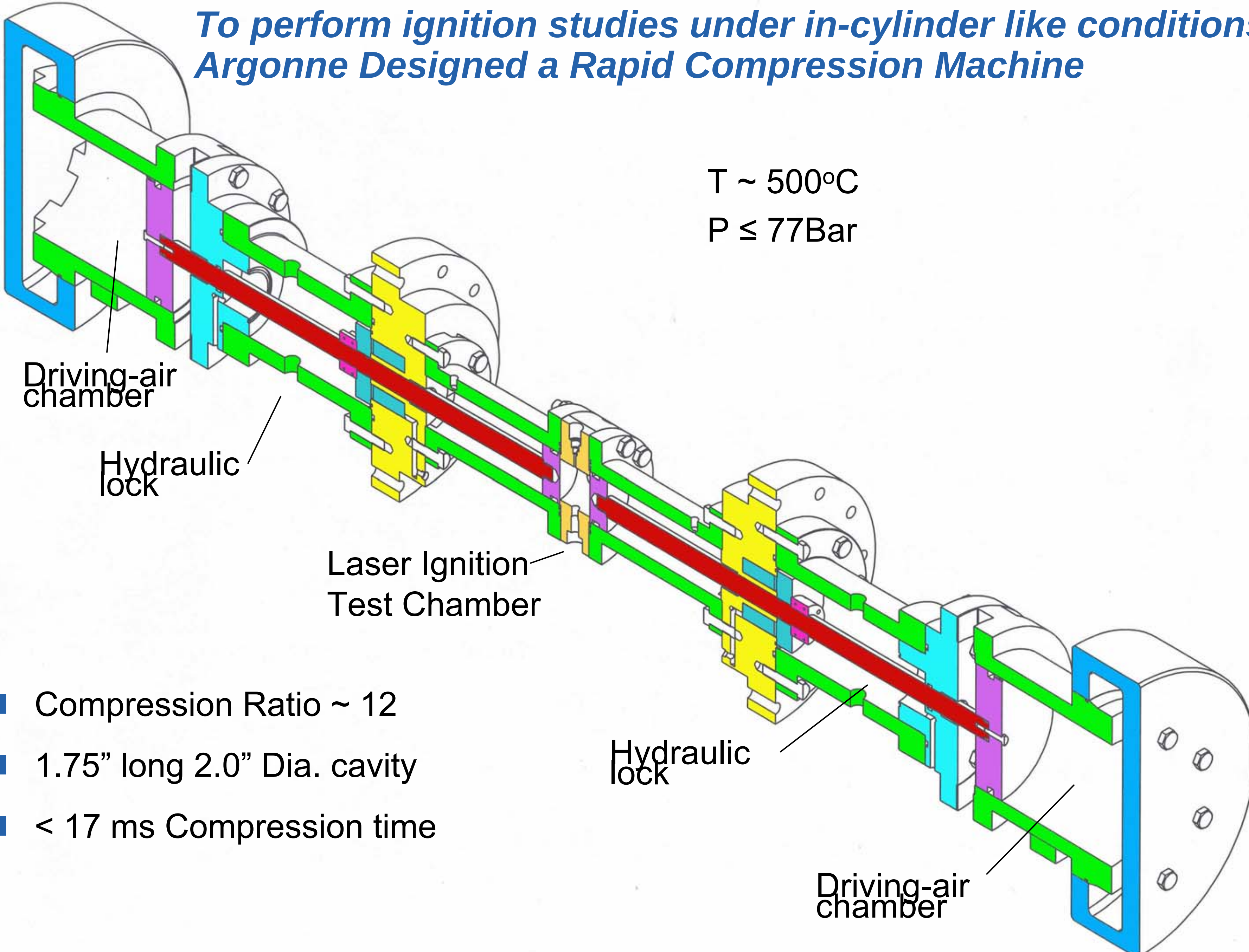


Boundaries of Operation

- Lasers can ignite mixtures at higher pressures
- Extensions in lean ignition limits could not be observed
- Ignition studies under engine-like temperatures (~ 500°C) are not possible with static chambers

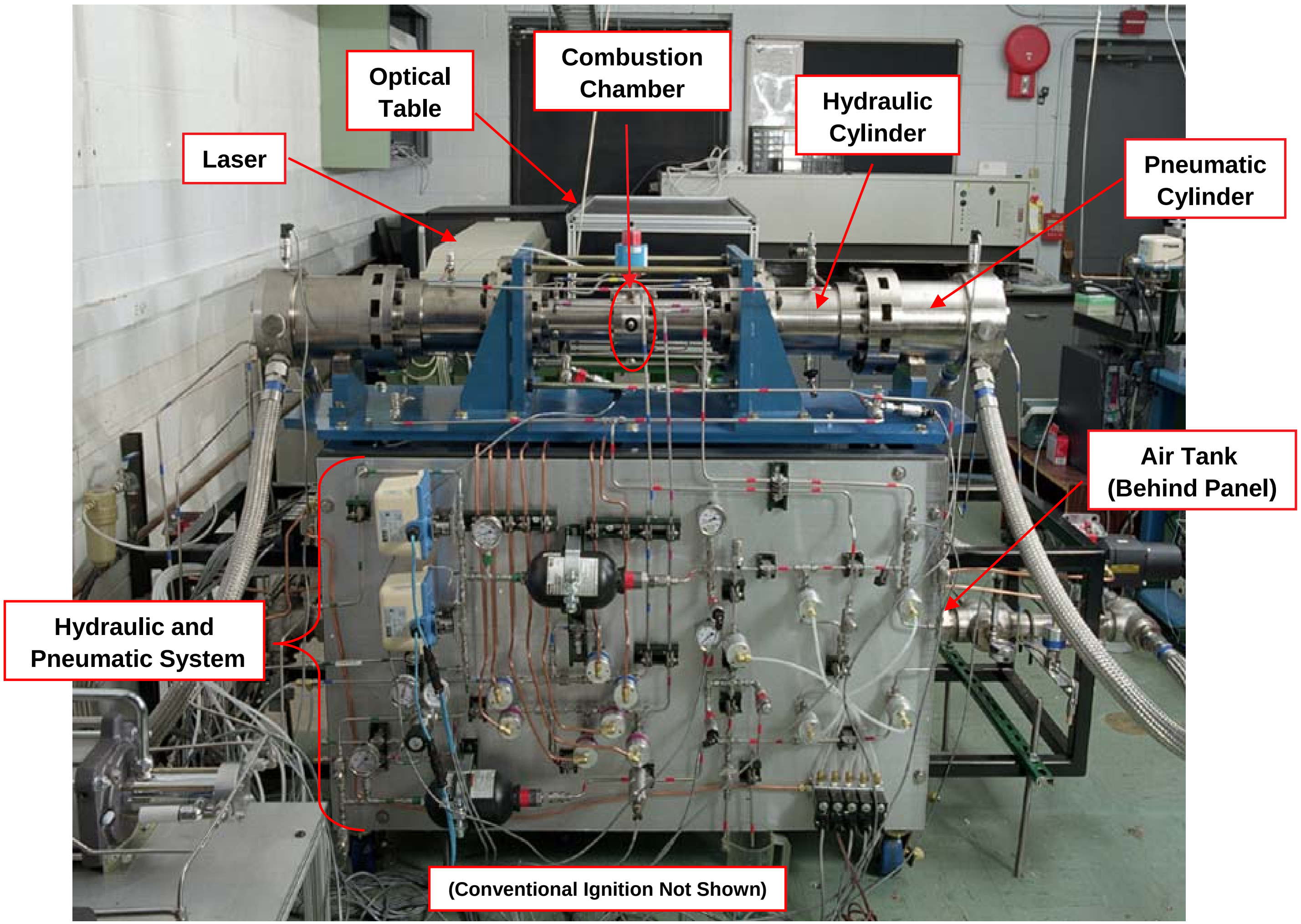


To perform ignition studies under in-cylinder like conditions Argonne Designed a Rapid Compression Machine

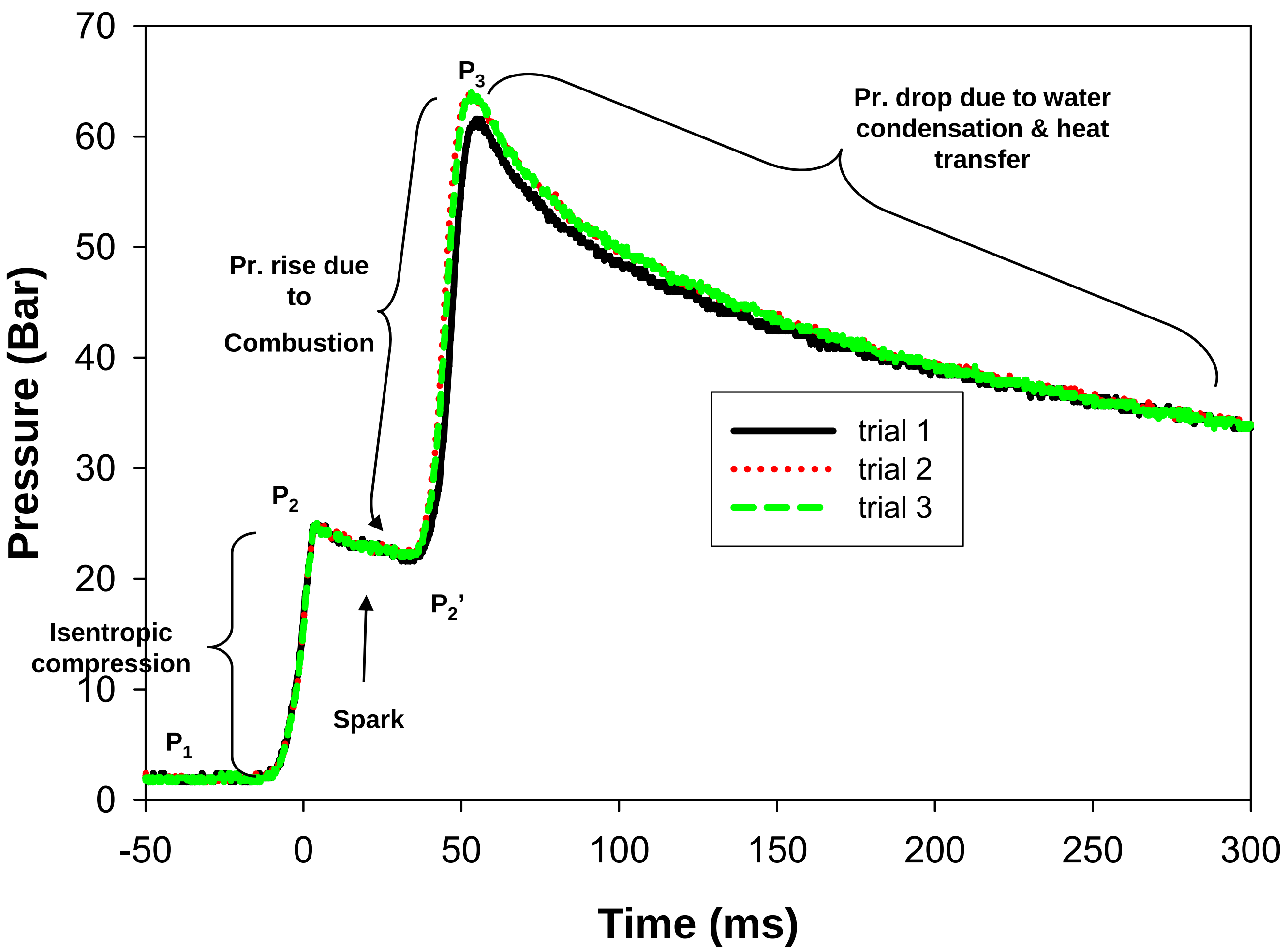


- Compression Ratio ~ 12
- 1.75” long 2.0” Dia. cavity
- < 17 ms Compression time

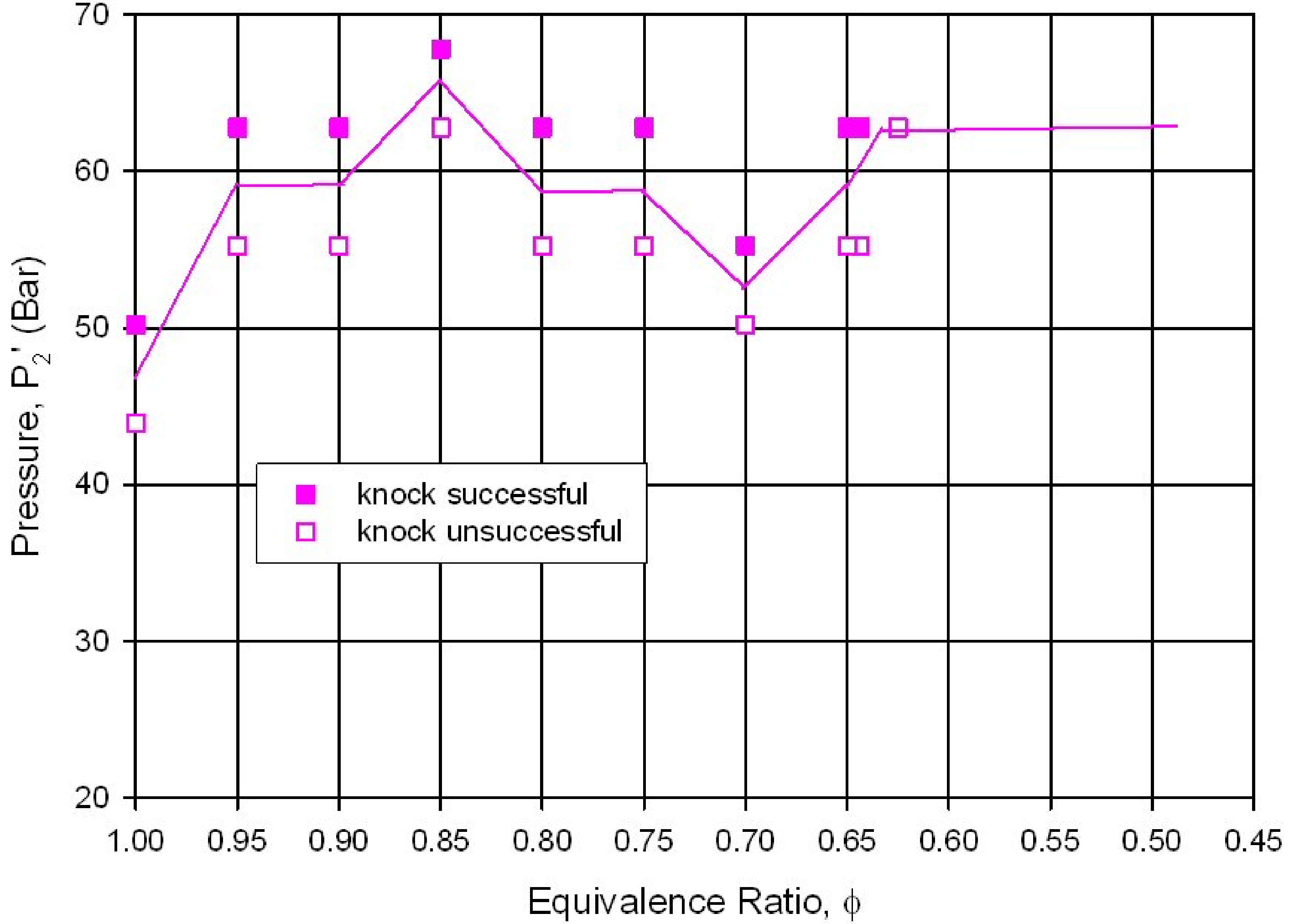
Argonne & DOE Provided the Necessary Funds to Build the Rapid Compression Machine



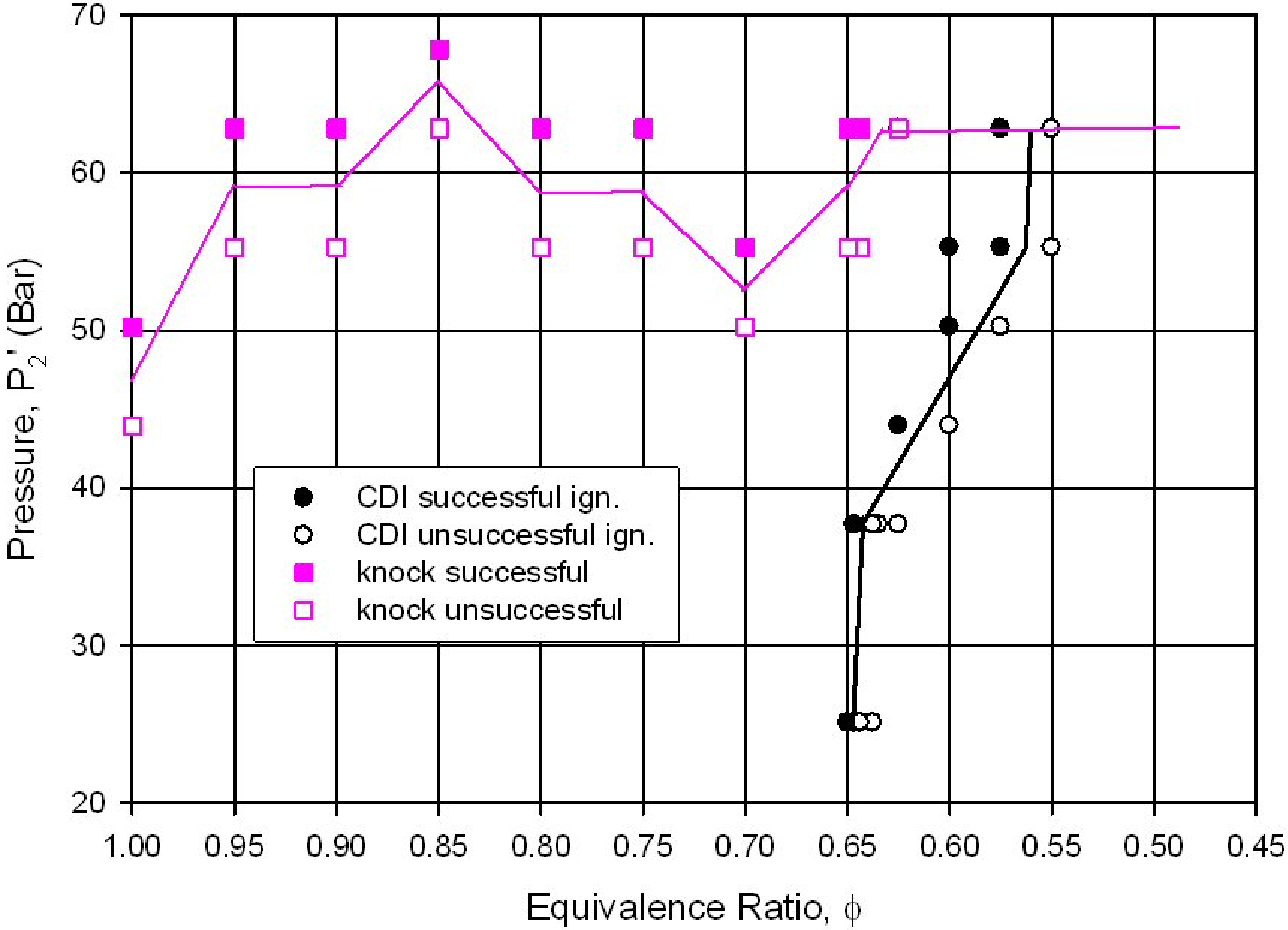
Typical Pressure Traces From the RCM



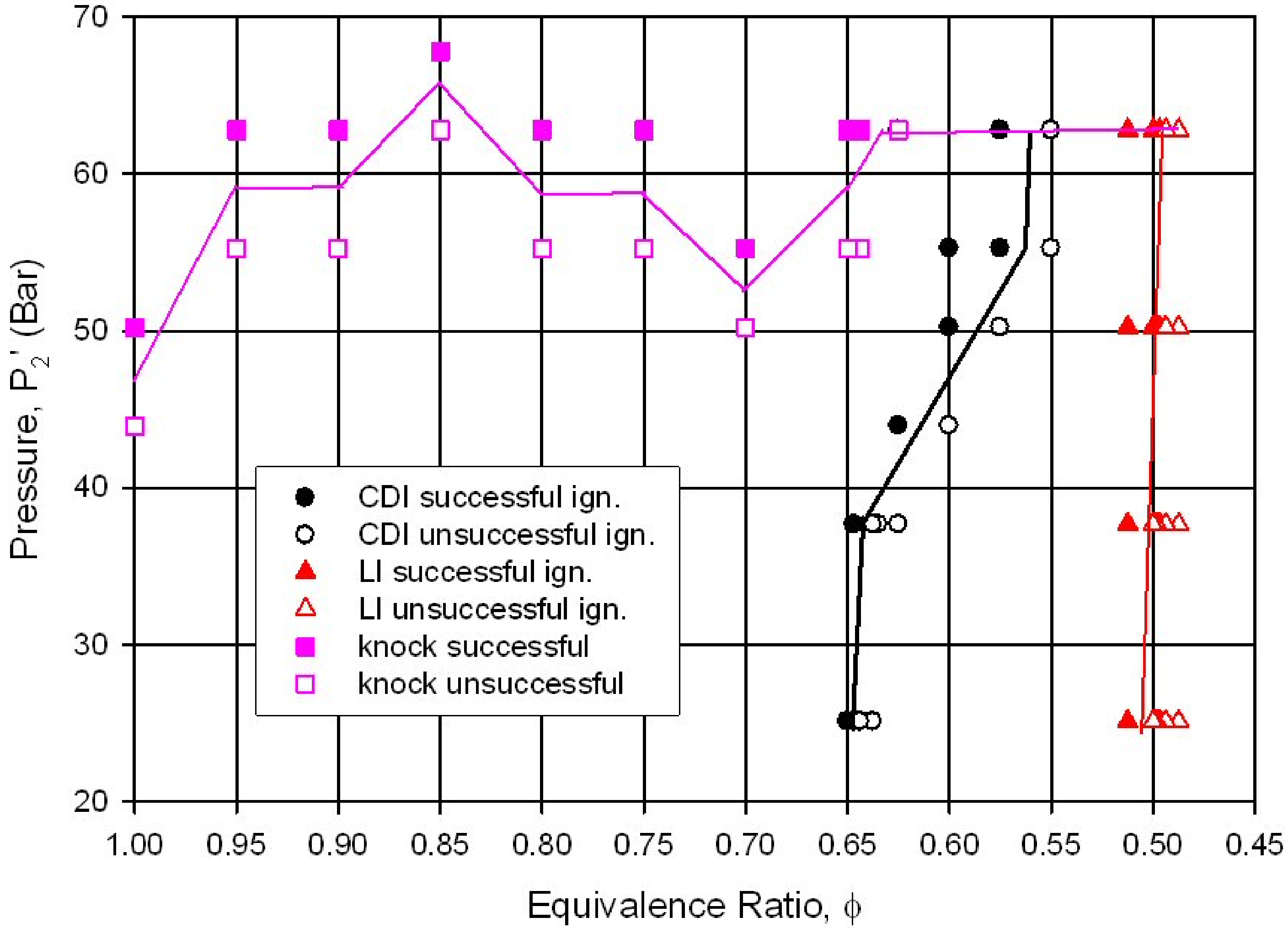
Self-ignition Limits



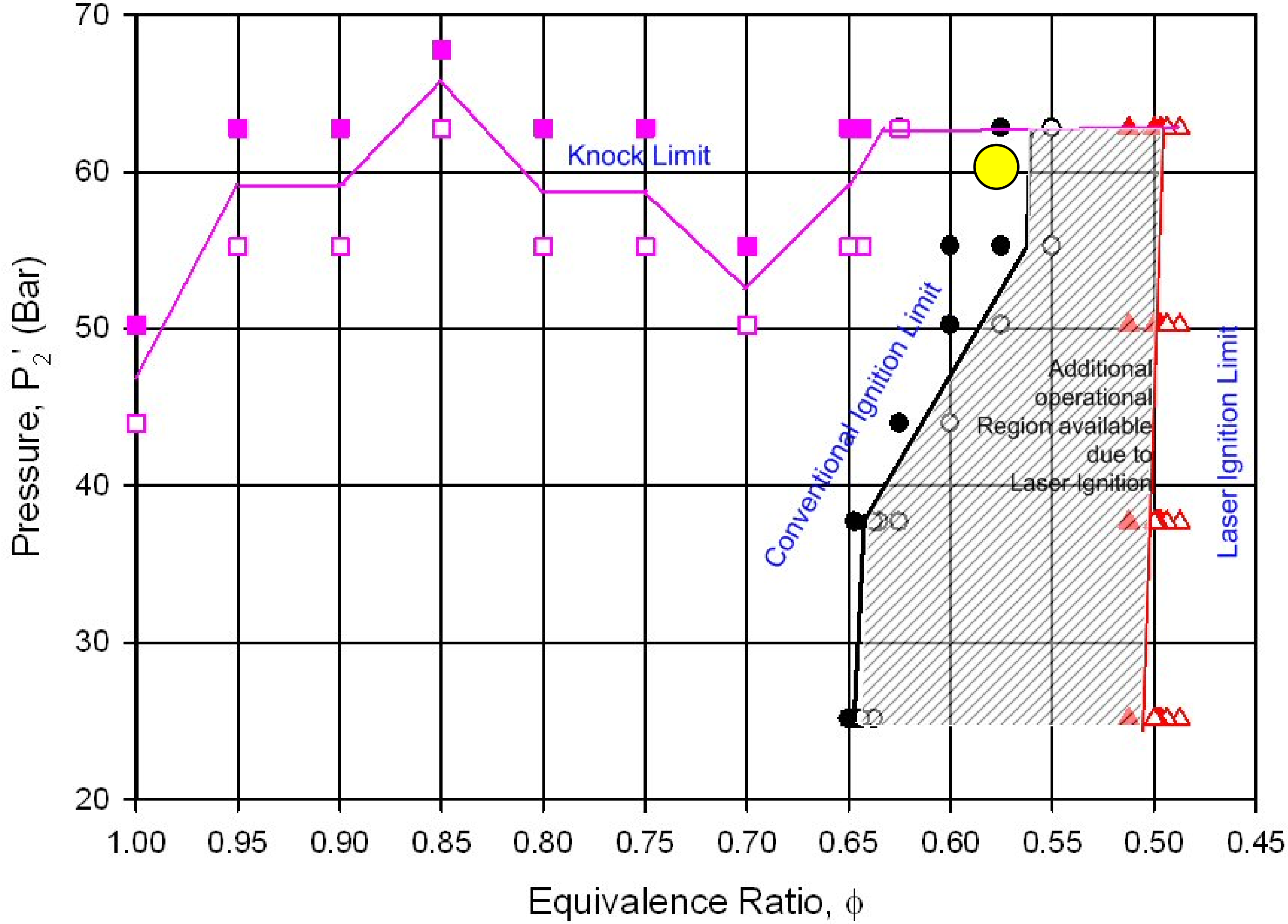
…+ Conventional Ignition Limits



…+ Laser Ignition Limits



Mixtures much leaner than those limiting conventional ignition can be ignited using laser ignition

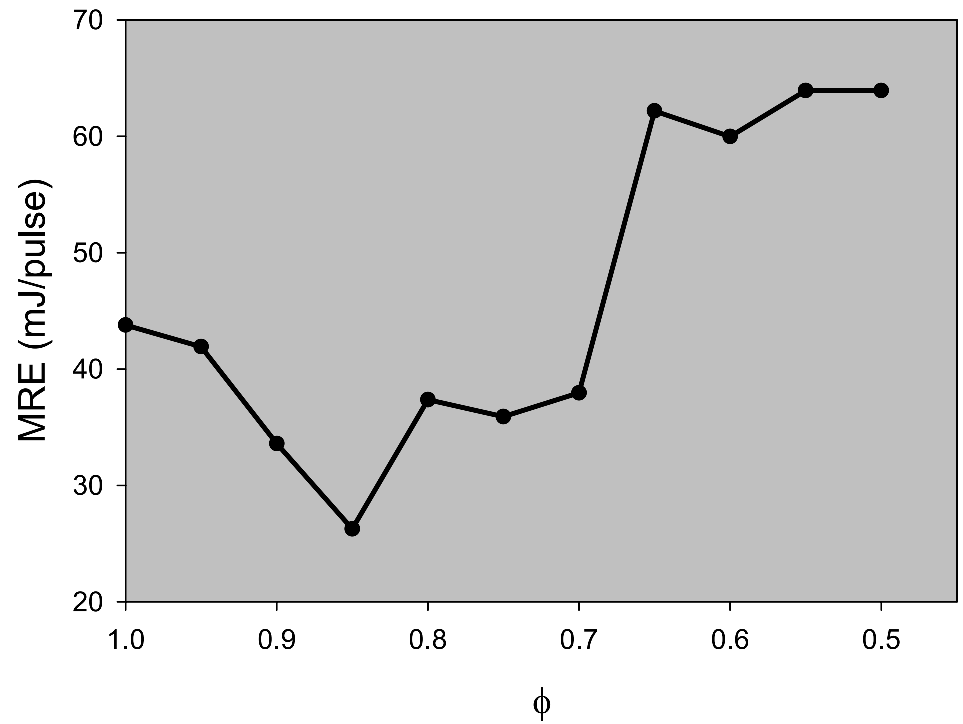


ASME ICES-1064

2005

Minimum Required (free space) Laser Energies

- A scan of MRE shows that an ignition system designed for ϕ = 0.5 and MRE = 65 mJ/pulse** will operate at all other equivalence ratios of Natural gas – Air mixtures



** MRE determined at 7ns pulse width, $M^2 \geq 3$, focal spot size 240 μm. Turbulence and velocities are comparatively high to equivalents in engines.

$P_2' = 37.7$ Bar

Task 2.3
Development of ALIS Components

Objective

Design and develop components required for a viable laser based ignition system by using information gained through task 2.2.

Functional Requirements for an Advanced Laser Ignition System for a Natural gas Engine Were Established.

Established Nov. 6, 2002 by Caterpillar, Cummins and Waukesha

Cost (current dollars)		
- First Cost (add $1/ekw for CSA requirement)	4.00	$ / kWe
- Life Cycle Cost (including system replacement at major)	0.25	$ / MWe-hr
- Repair Costs to 1st Engine Overhaul	0.15	$ / MWe-hr
Performance		
-Maximum ignition pressure (peak cylinder pressure)	220	bar
-Minimum air/fuel ratio	0.9	λ
-Maximum air/fuel ratio (w/swirl)	2.5	λ
- Maximum methane number (landfill capable)	140	
- Ignition timing repeatability (non-mechanical)	0.08	° crank
- Ignition timing accuracy (non-mechanical)	0.08	° crank
- COV (steady state, 0.5 g/bhp-hr NOx, 25 bar BMEP)	<1.0	%
- RPM maximum (overspeed)	125	% of rated
- RPM minimum (cranking)	50	rpm
- Full Load range (minimum – maximum)	10 – 25	bar
Ignition System Durability		
- Life to replacement for ignition module and harness	80,000	hrs

Functional Requirements for an Advanced Laser Ignition System for a Natural gas Engine Contd.

Reliability		
- Ignition System (continuous duty)	6000	MTBF (hrs)
- Ignition System Reliability (peaking / standby)	3000	MTBF (hrs)
Environmental		
- Vibration	10	G's (rms)
- On-engine Temperature Range	-40C to 130C	°C
- Ambient Temperature	-40C to 48C	°C
- In-cylinder temperature	2200	°C
Physical		
- Size (max of any one piece)	0.015	M^3
- Weight (max of any one piece)	10	kg
- Number of cylinders (scalable)	4 – 20	cylinders
- Power source	24	VDC
Mounting		
- System Location	All systems on engine	
Mean Time to Repair		
- Continuous duty	6000	hrs
- Peaking / standby duty	3000	hrs

Additional Requirement (2005):

A capability to vary ignition timing on individual cylinders ± 6 Crank Angle Degrees (CAD)

Lasers of Required Performance Characteristics are Readily Available

- Laser performance targets
  - 532 / 1064 nm
  - < 7ns pulse width
  - 90 Hz repetition rate
  - 65 mJ/pulse
  - $M^2 < 5.0$
  - 10 – 40°C operating range
  - Compact laser head with low power requirement
  - lifetime > 10^9 shots

Model: Centurion
Manufacturer: Big Sky Laser, Inc.
DPSSL, 100 HZ, 45 mJ/pulse

- A survey performed showed that Diode Pumped Solid State Lasers meet the above requirements for engine ignition applications

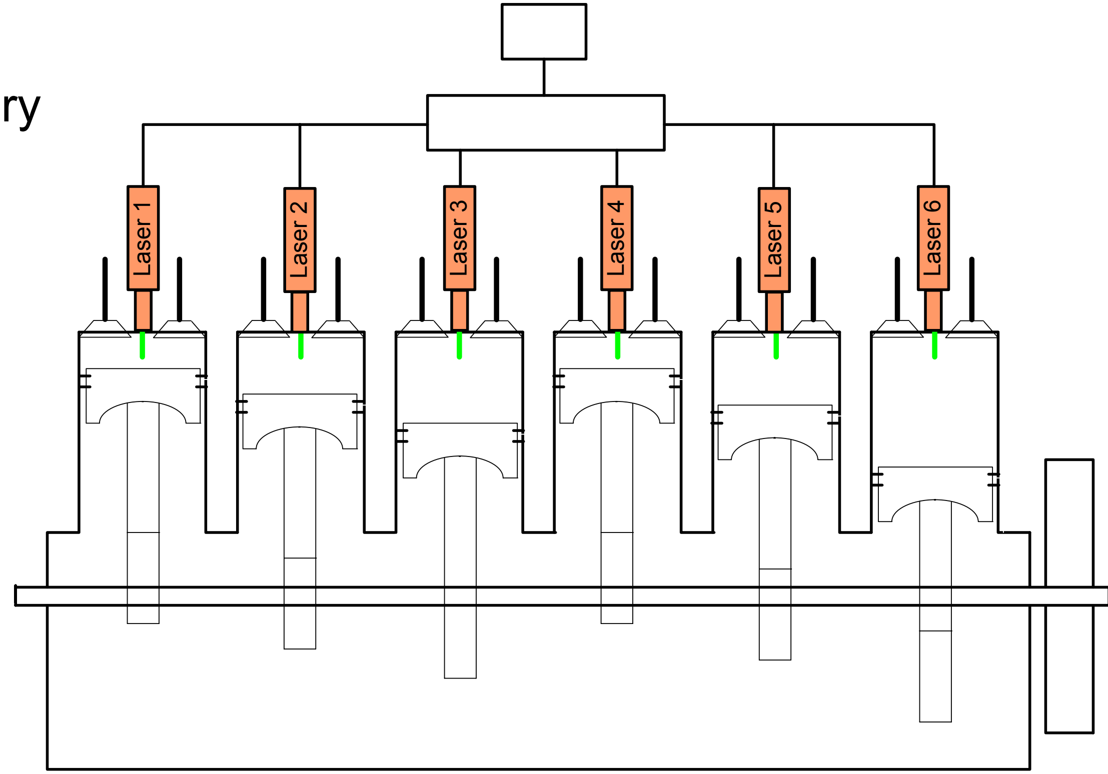
- A flash lamp pumped Q-switched compact laser, already available in the lab (Model CFR 200 from Big sky laser, Inc.), is being used for ALIS development and demonstration. Flash lamps limit the operation of such lasers to < 8 days of continuous operation.

Approach 1: *A laser-per-cylinder (NETL)*

A small laser is mounted directly on each cylinder of the engine.

Advantages:

- Allows a free space beam delivery
- Requires smaller laser output energies to generate spark

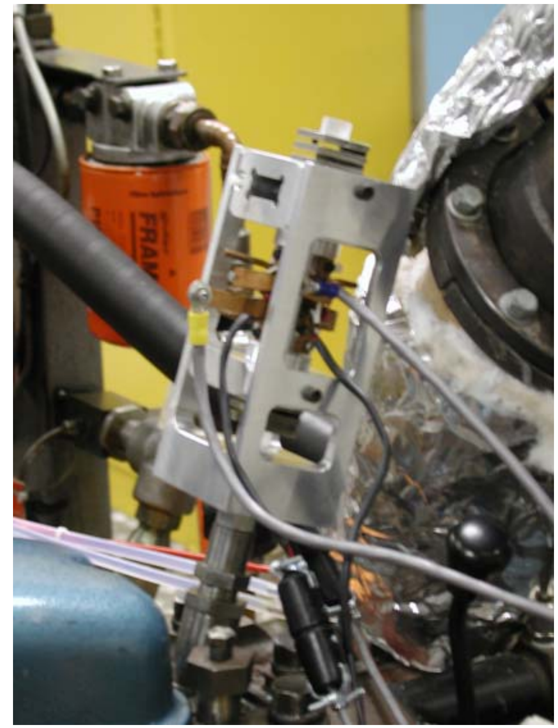


Issues:

- Lasers must withstand engine vibrations
- Laser heat dissipation
- Expensive

Approach 1: Develop a small DPSS laser

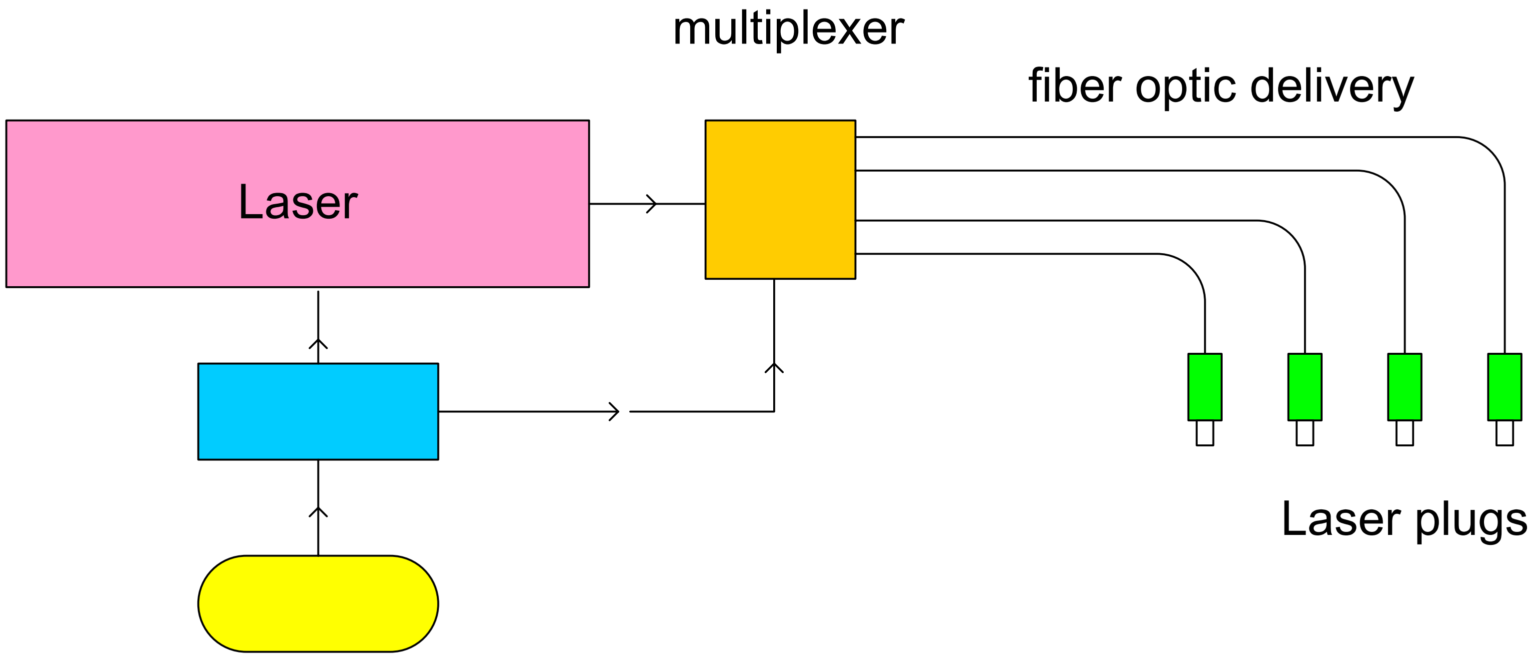
- Used computer modeling to provide guidance
- Tested different combination of lasing materials andoptics
- Consistent sparking achieved in lab
- Limited success on engine so far
- Efforts underway to improve heat management



NETL

Approach 2: Multiplexer approach (ANL/CSU)

Output of single laser distributed among various cylinders of the engine.



<u>Advantages:</u>

- Use commercially available lasers
- System isolated from engine vibration
- Low overall cost

<u>Components to be Developed:</u>

- Laser plug
- Multiplexer
- Fiber optic beam delivery

Numerous Designs of “Laser Plugs” Have Been Developed

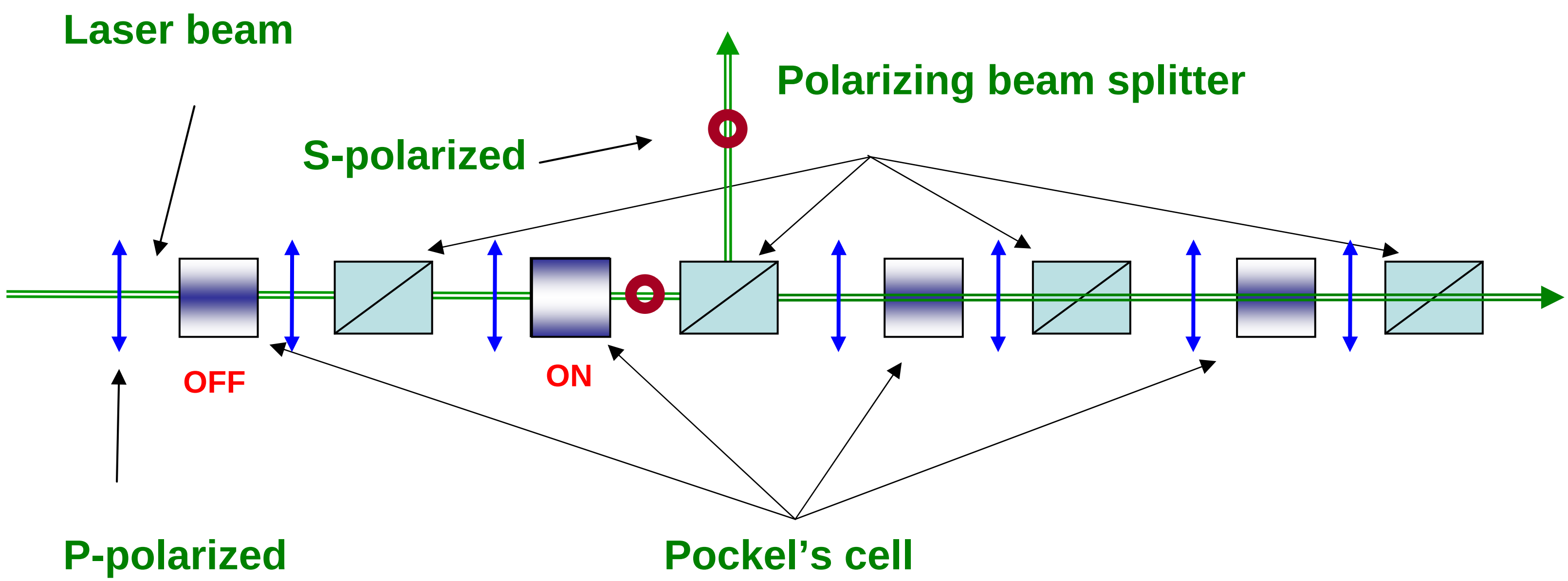
- Sapphire Lenses for laser transmission
- Withstand in-cylinder pressures and temperatures
- Ablate any deposits
- Same foot print as standard plugs

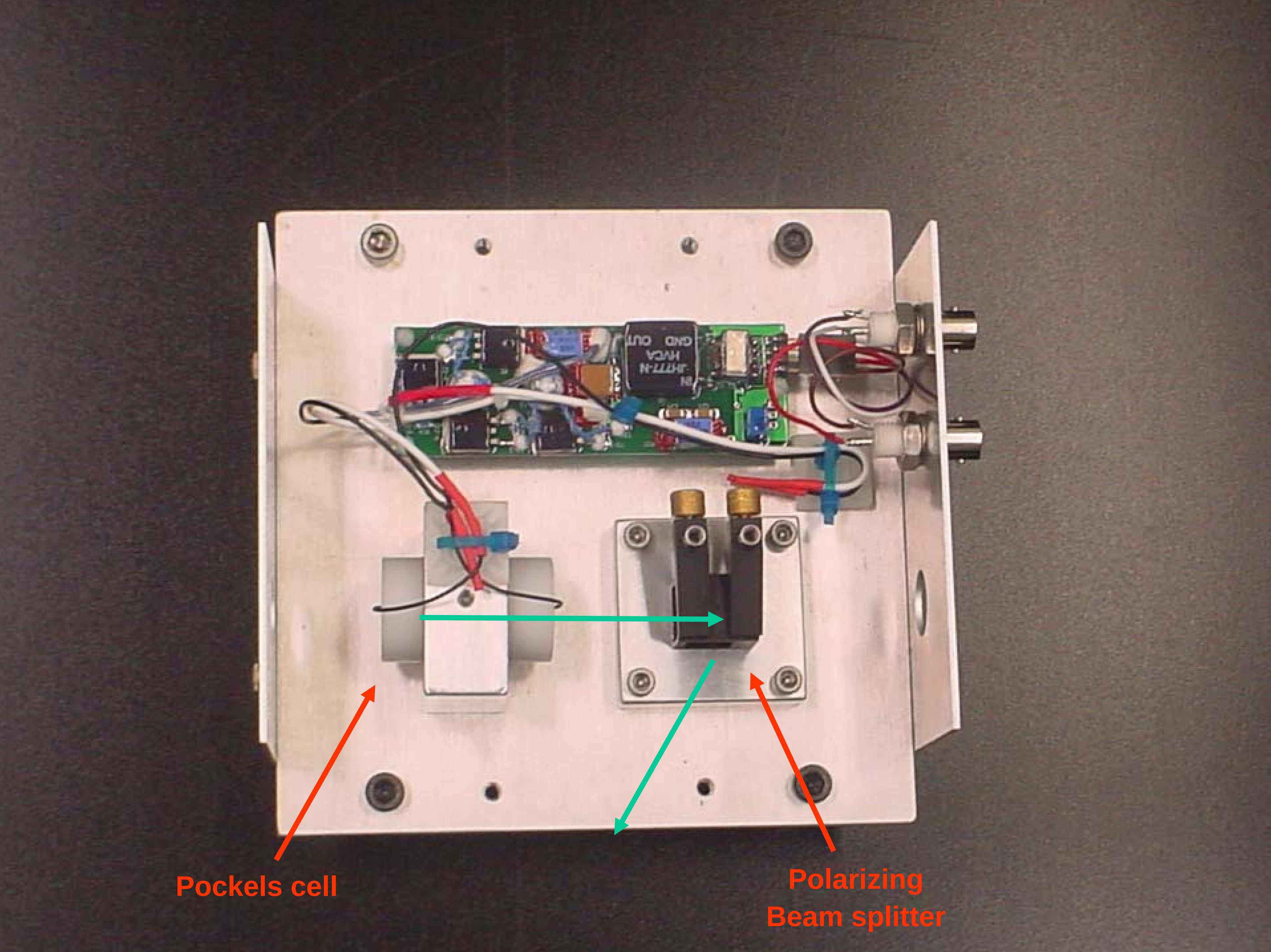
Multiplexer Development

A Multiplexer must be:

- Low-cost
- Durable
- Allow Ignition timing variation on each cylinder ±6 CAD
- Allow ignition timing variation 0 – 48 Crank Angle BTDC

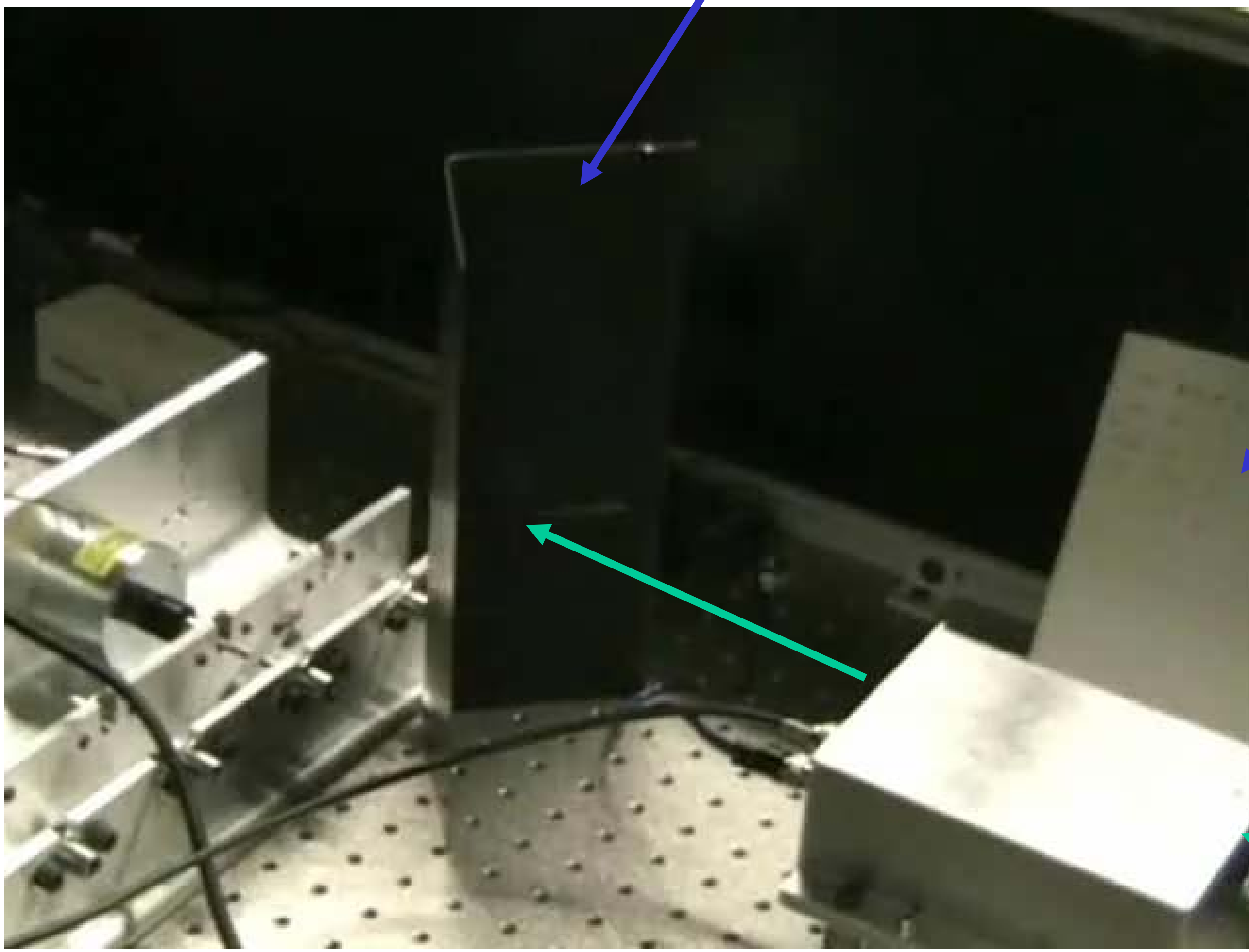
Mux 1: Electro-optic Switch (Pockel's Cell)




Pockels cell
Polarizing
Beam splitter

Mux1: Electro-optic Switch

Beam Block



Target

Laser Beam

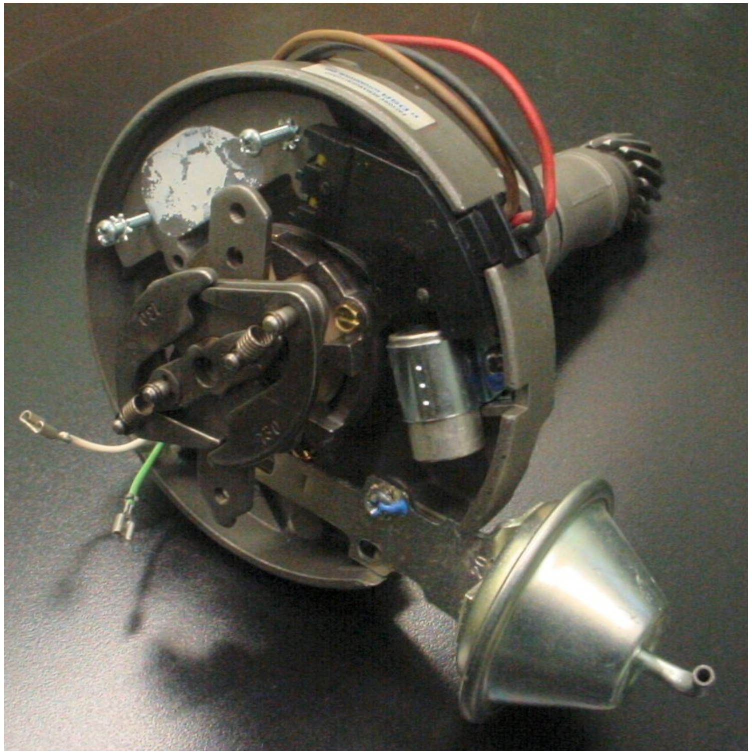
Issue: High-cost; ~ $2000 per channel

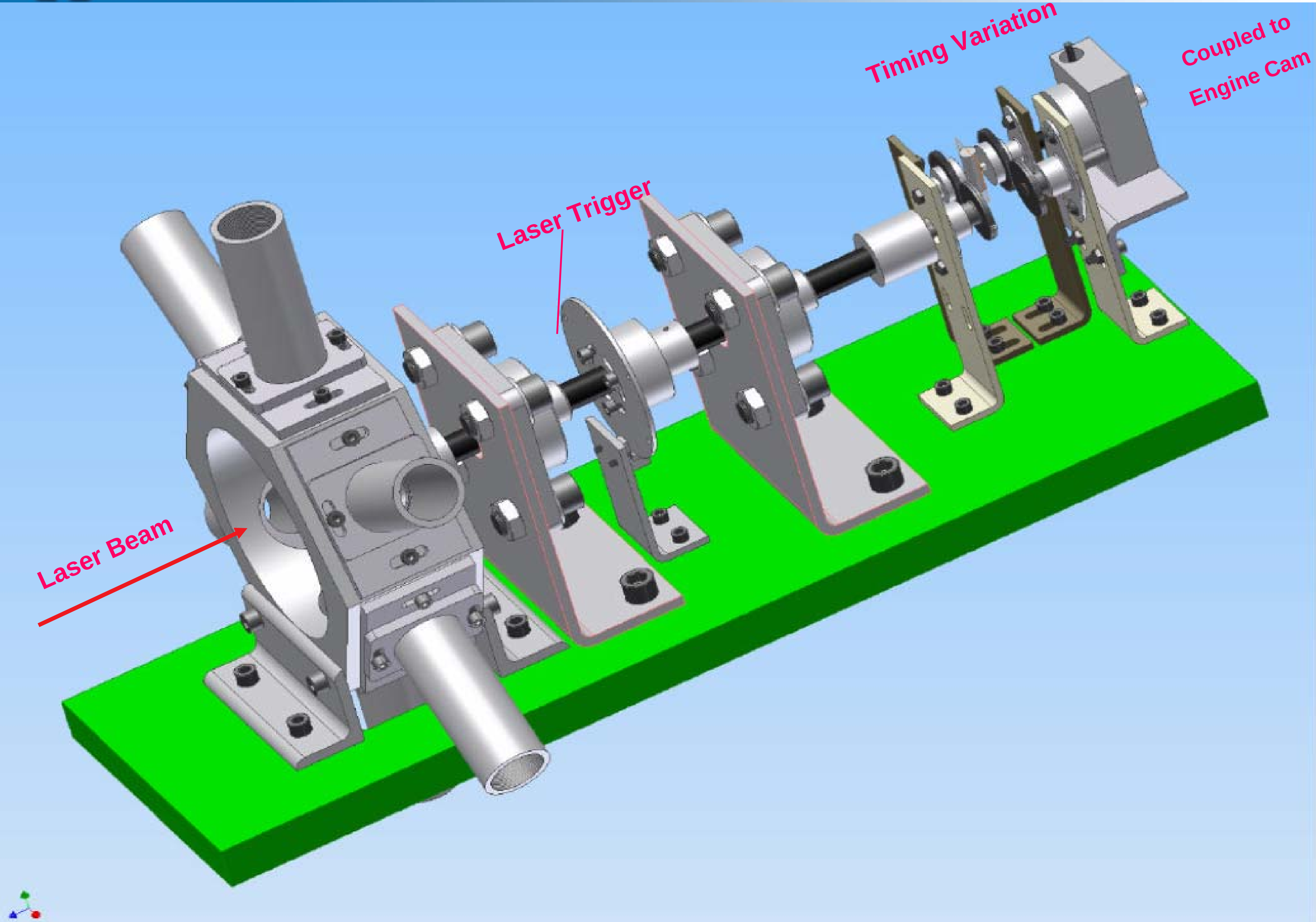
Mux2: Rotating Mirror Multiplexer

- Design based on an automotive distributor

<u>Advantages</u>

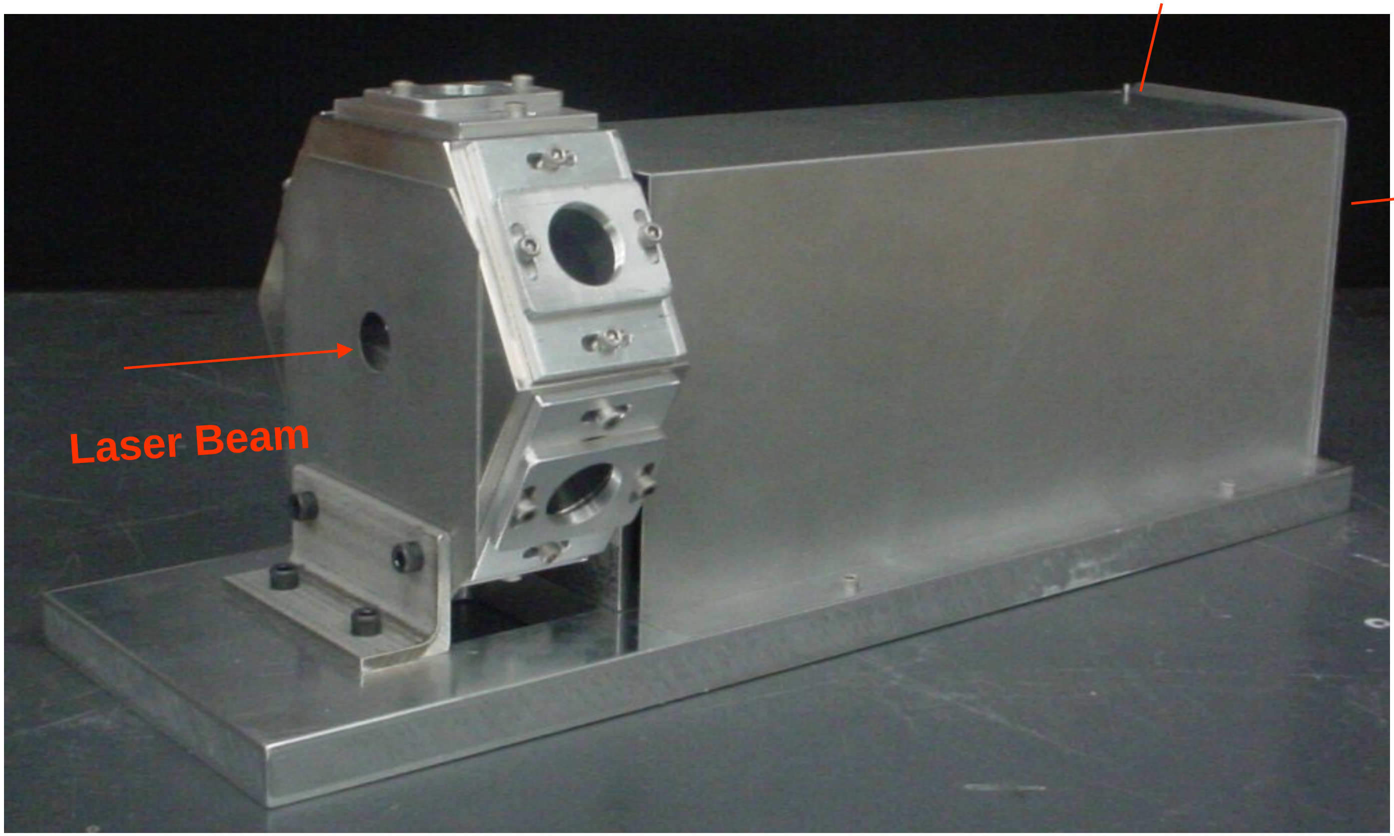
- Low-cost
- Simple




Timing Variation
Coupled to
Engine Cam
Laser Trigger
Laser Beam

Prototype has been built. Performance will be evaluated soon

Ignition advance/ retard

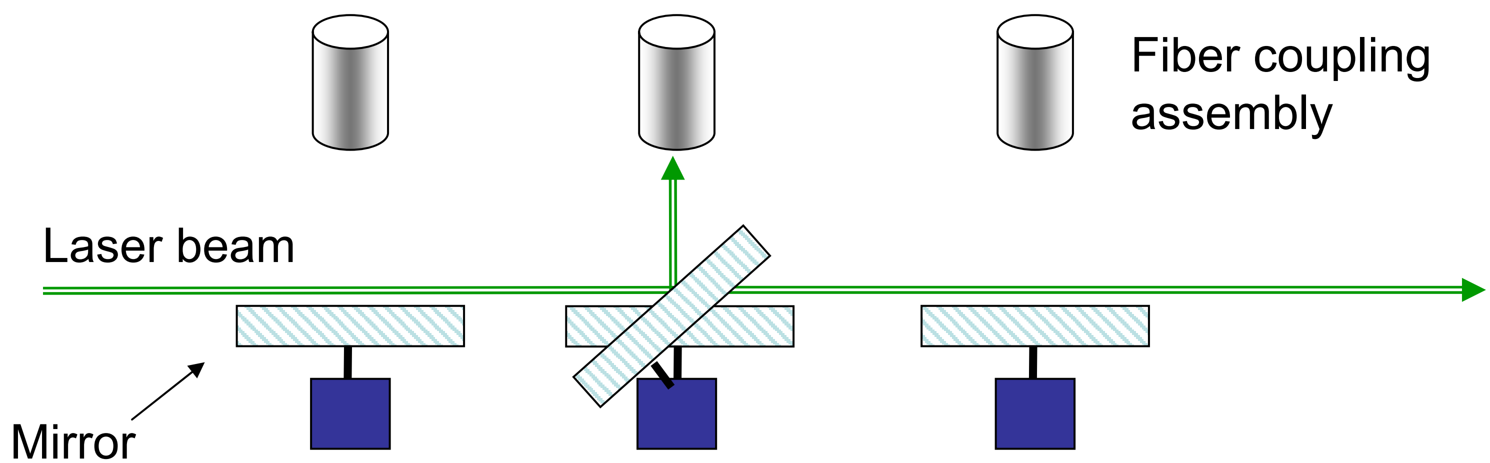


Coupled to

cam shaft

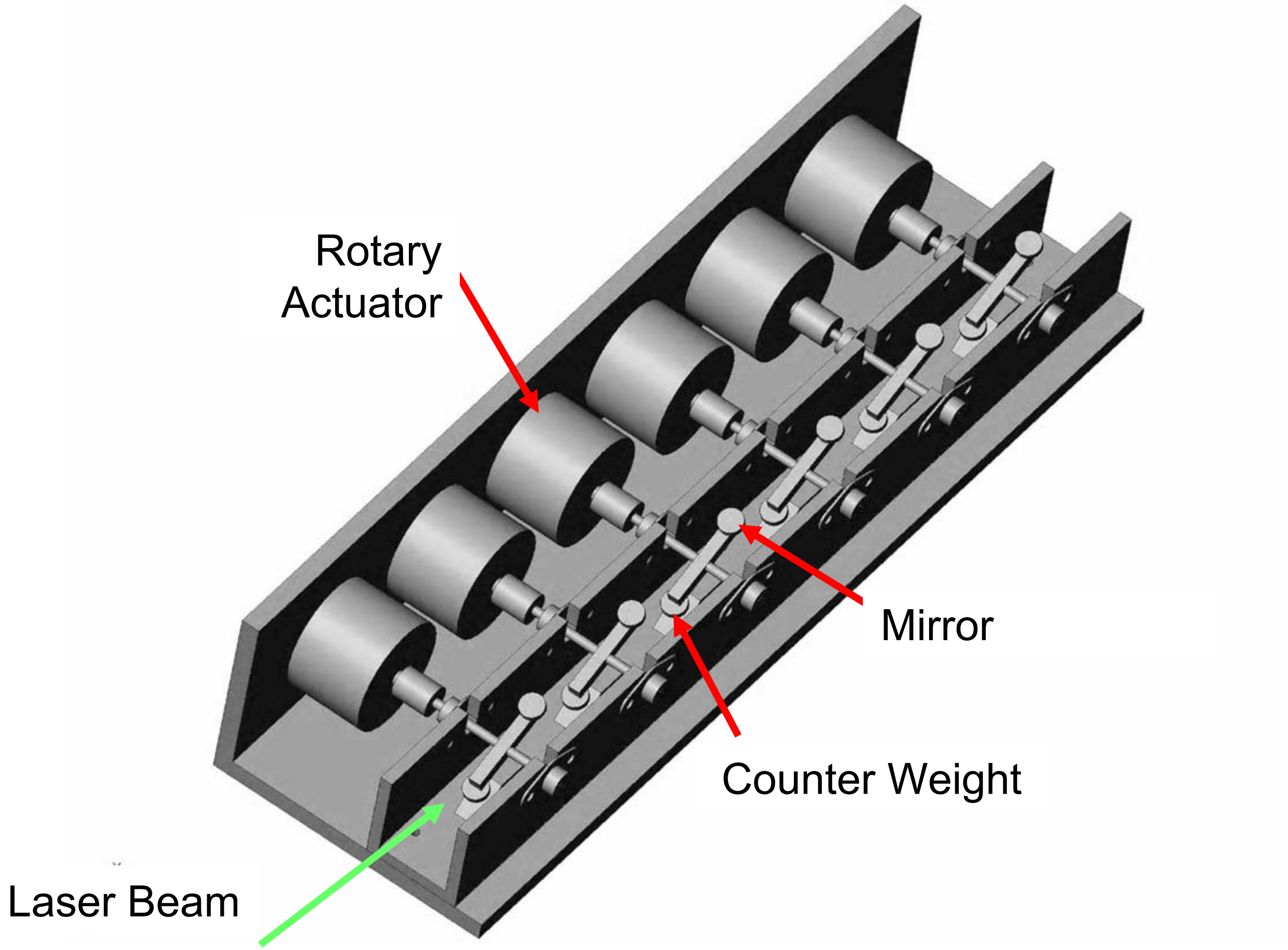
- Designed to run a 6 cylinder engine
- However, individual cylinder timing variation is difficult

Mux3: Flip-flop Multiplexer

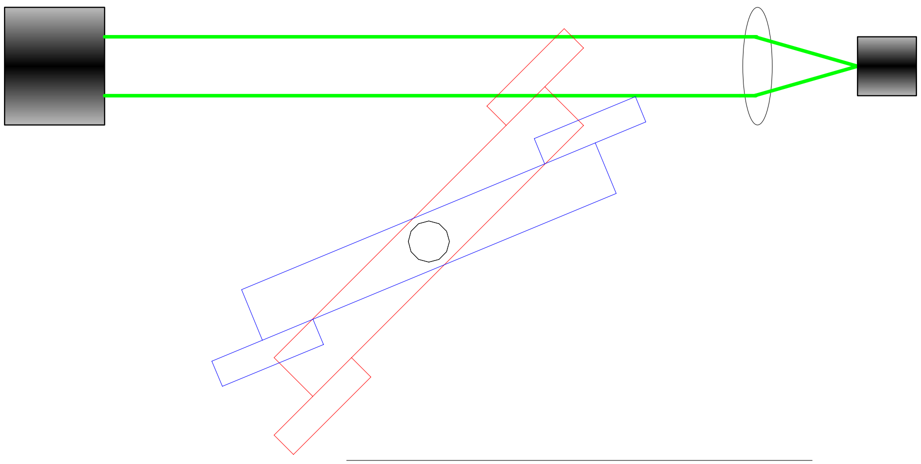


- To operate a 6-cylinder engine, each mirror must have a 11 ms rise or fall time.
- After some analysis, a leading automotive manufacturer was contacted who provided some prototype actuators

1-channel of the prototype was built and tested



The Flip-flop Design Exceeds our Performance Targets



Target

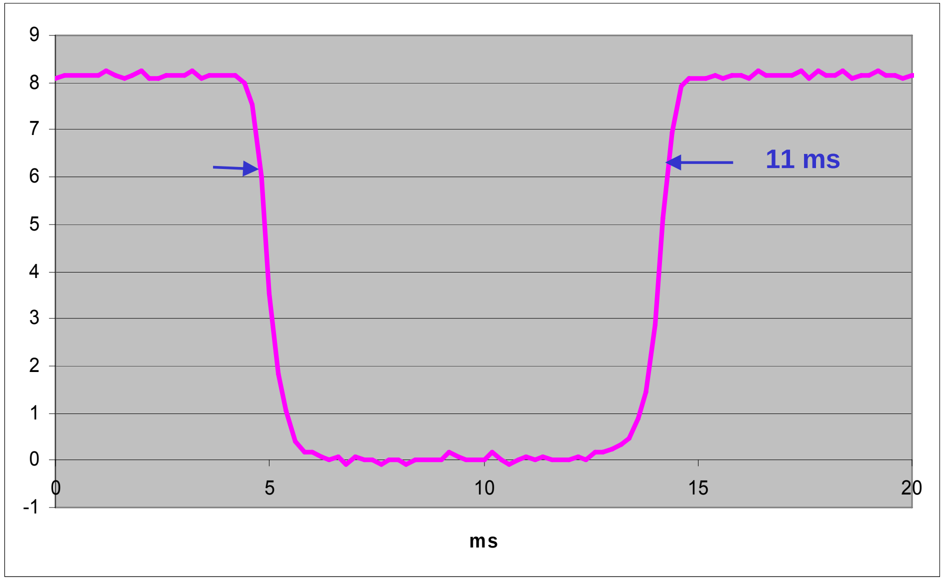
Rise or fall time = 11 ms

Measured

Rise + fall time = 11 ms

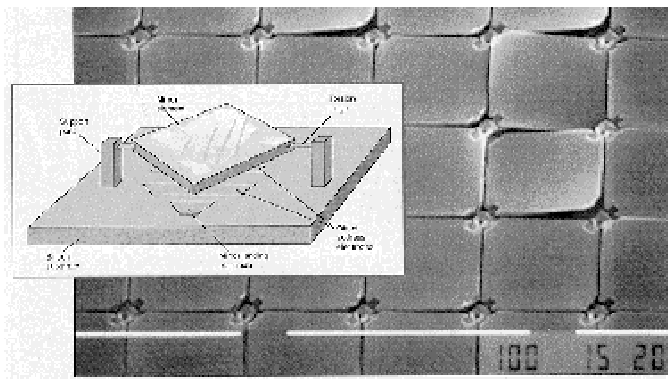
200 μs dwell at end of stroke ideally sufficient for laser firing

System exhibits no bounce



Future Plans for Multiplexer Development

- Obtain required instrumentation and characterize Mux3 for pointing stability



Texas Instruments: Digital Mirror Device (DMD)

(768 x 576 and 2048 x 1152) are available.

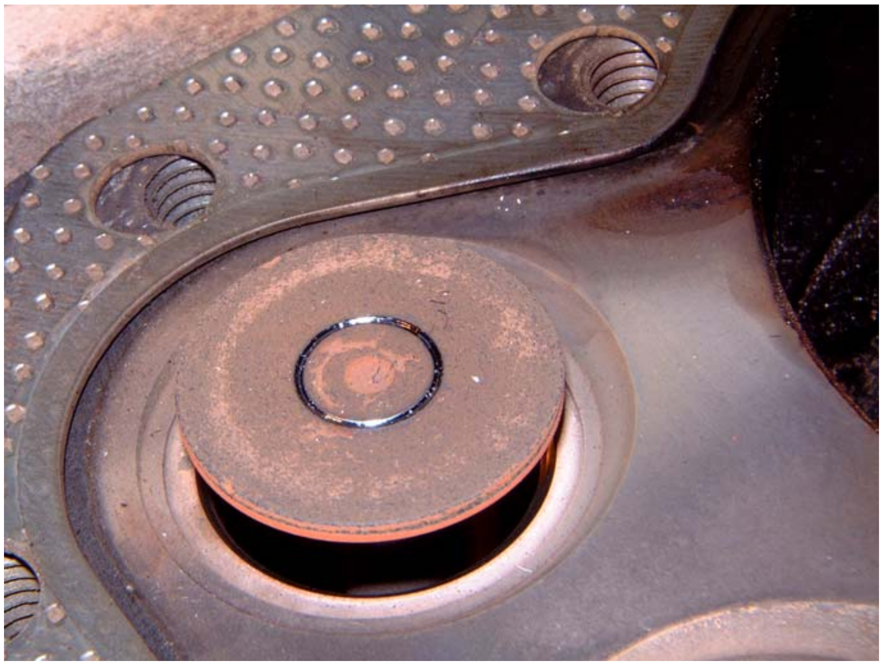
Response time = 10 µs.

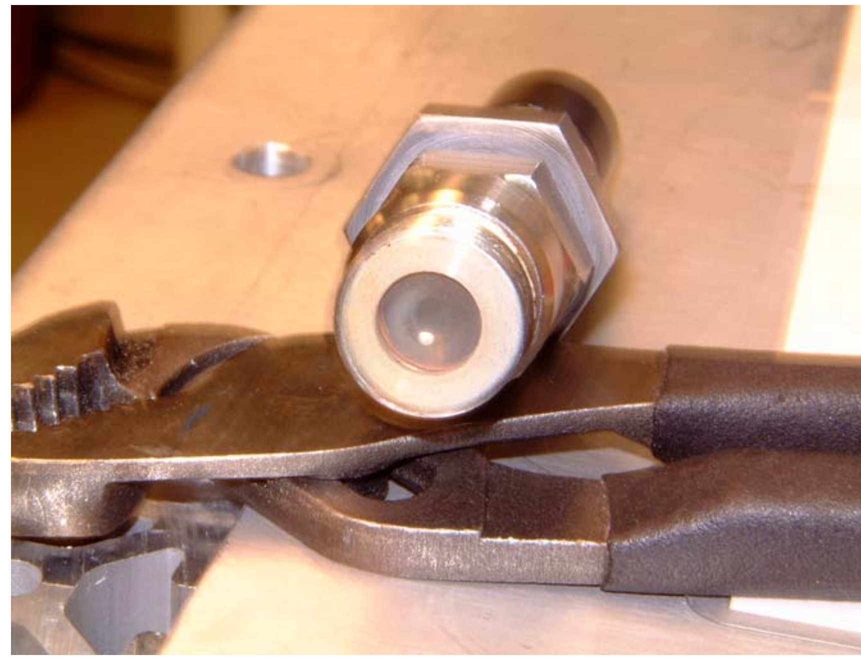
$\pm$ 12 degrees optical.

- Wrap up multiplexer development

Fiber optic Beam Delivery Development

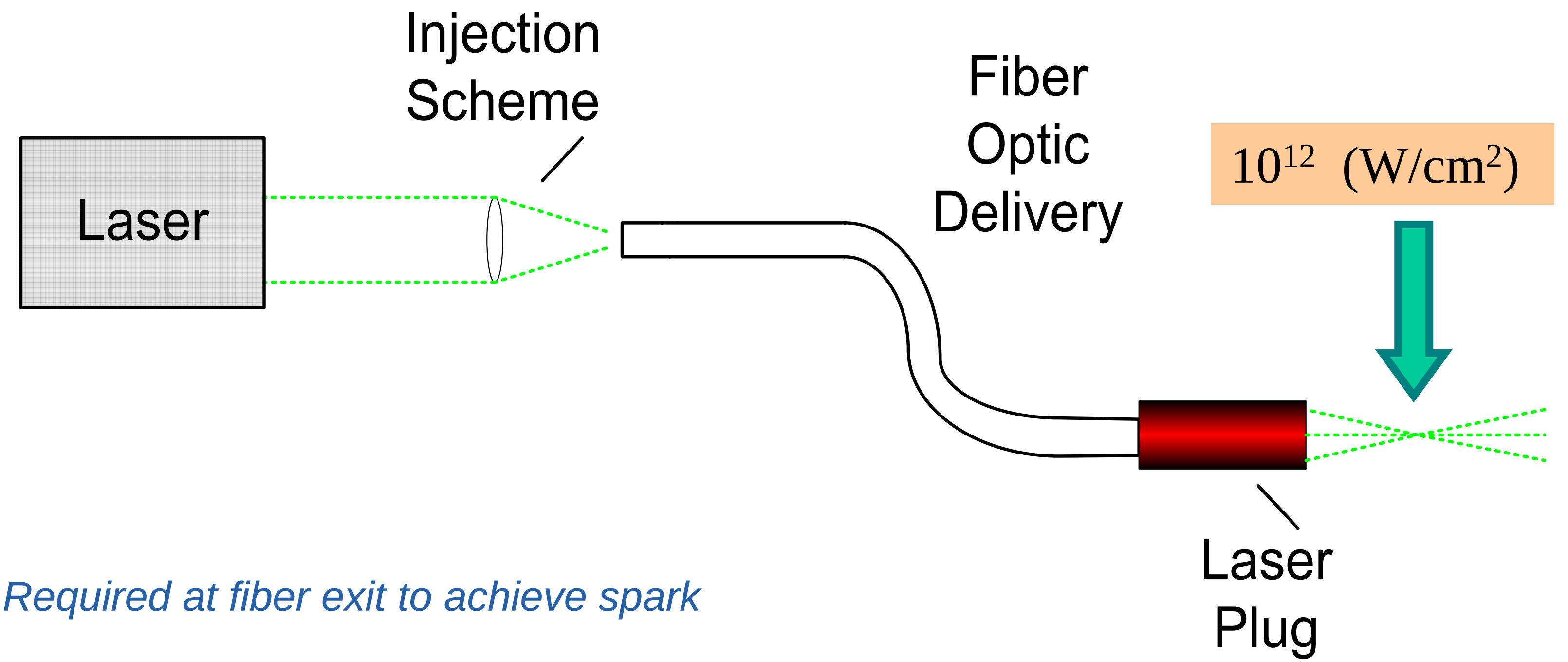
Laser Ignition Using a Solid Target is <u>not</u> an Option





- Engine could be operated < 12 Hrs. while focusing on a exhaust valve surface
- Target material ablates when plasma forms
  - *.5 mm thk 304 stainless 500,000 shots*
  - *.5 mm thk 316 stainless 600,000 shots*
- Lens fouling occurs with deposition of ablated material

ALIS Simplified

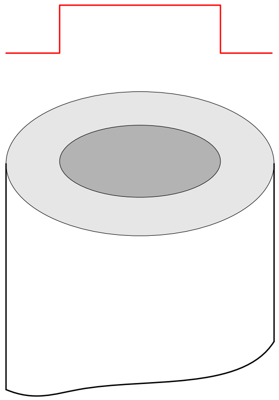


Required at fiber exit to achieve spark

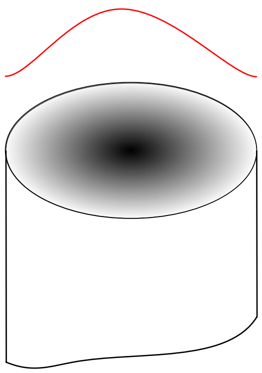
(1) *High-beam quality,*
(2) *High-laser energy and*
(3) *Low-divergence*

Solid Core Fibers

Step Index



Graded Index



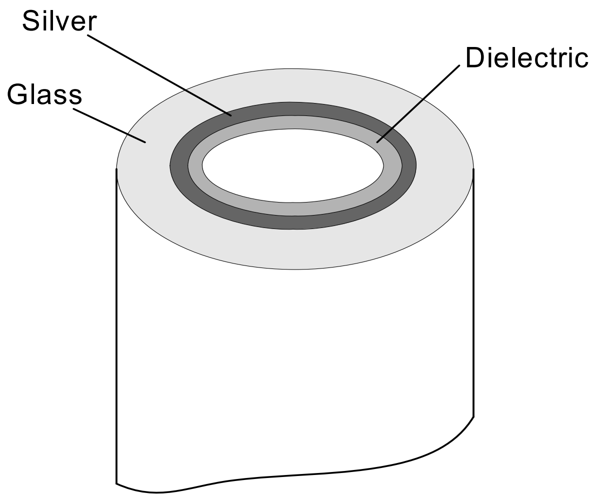
- Damage threshold ~ 5 GW/cm^2
- Readily available
- Successfully transmitted > 30 mJ, 8 ns pulses
- However, could not produce air breakdown

- Better beam quality at output
- Large core fiber commercially available
- Damage Threshold very low

n

Hollow Core Fibers

Hollow Glass Waveguides (HGWs)



- Damage threshold ~200 GW/cm^2
- Transmits 40X more power than solid core fibers.

- **Initially developed for Infrared lasers**
- **Performance recently extended to Nd:YAG lasers**
- **Beam quality depends on fiber bending**
  Bending Loss $\propto$ 1/Bend radius
- **Transmission losses depend on Core Diameter**
  Transmission Loss $\propto$ Core Radius^{-3}

Sparking was Easily Achieved in the lab Using HGWs

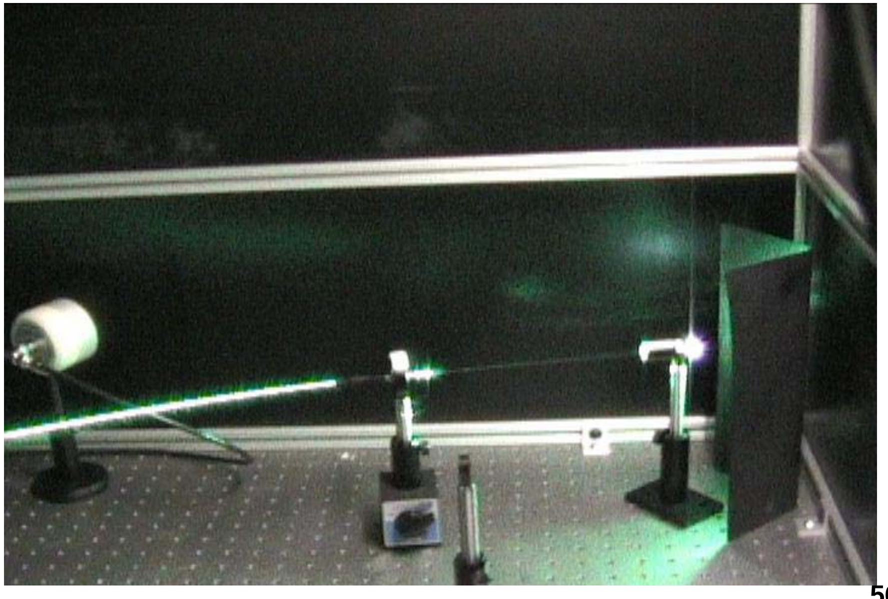
- HGWs tested for transmission loss

  Proprietary - Polymicro (Tucson, AZ)

  Ag/ CdS - Prof. Jim Harrington, Rutgers University

  Ag/COP - Prof. Yuji Matsuura, Tohoku University

- Transmission loss vs. Flexibility
  - 700μm was the best compromise



2.4 Ignition Tests in a Single-Cylinder Engine

ANL

Sreenath Gupta

Bipin Bihari

SwRI

Jess Gingrich

Jack Smith

Objective

- Determine the relative merits of Laser Based Ignition over conventional coil based ignition system in the operation of a natural gas engine.

- Evaluate the performance of ignition systems being developed

Engine Tests at SwRI

Bombardier BSCRE-04

1-cyl research engine

Bore x Stroke: 9” x 10.5”

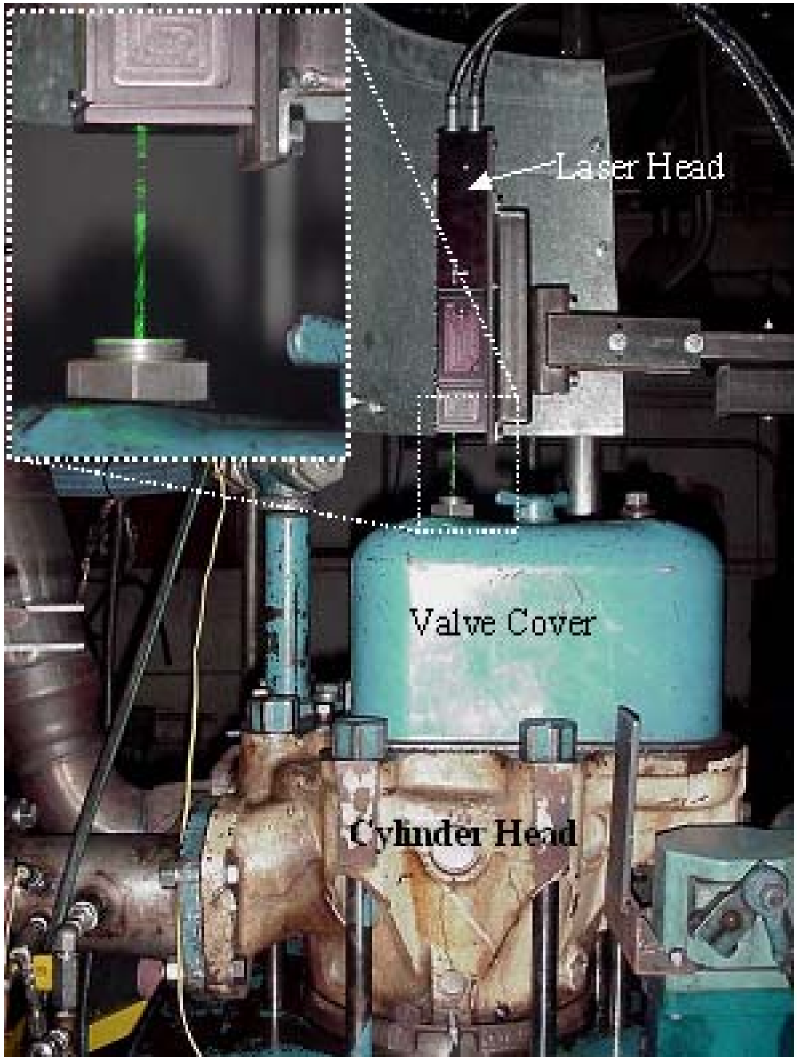
Compression Ratio = 9.3

The test matrix includes

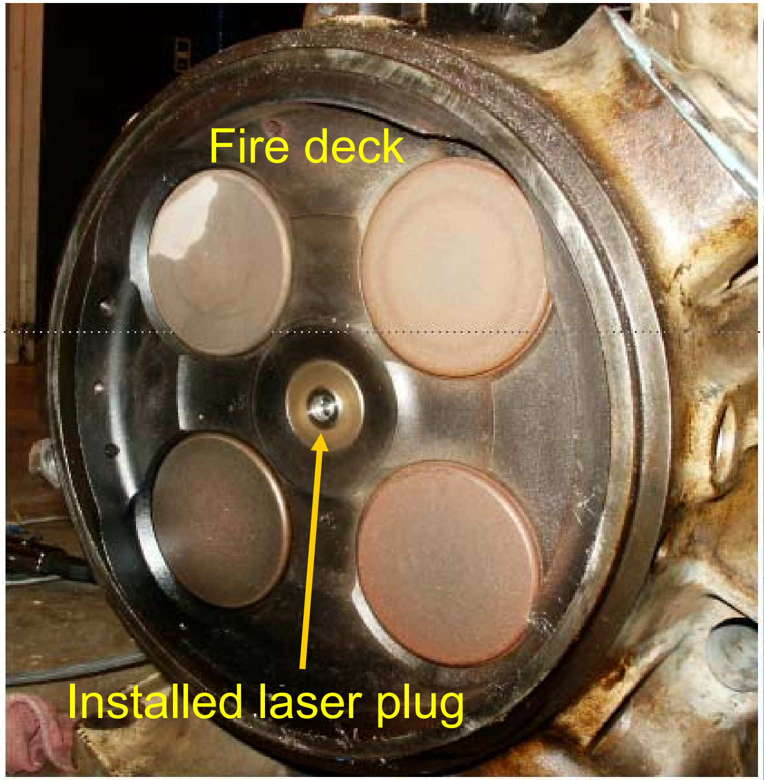
- **Conventional ign. tests** **- Altronic CD200 CDI system**
- **Free-space laser ign. tests** **- a compact laser**
- **Fiber-coupled laser ign. tests** **- fiber + compact laser**

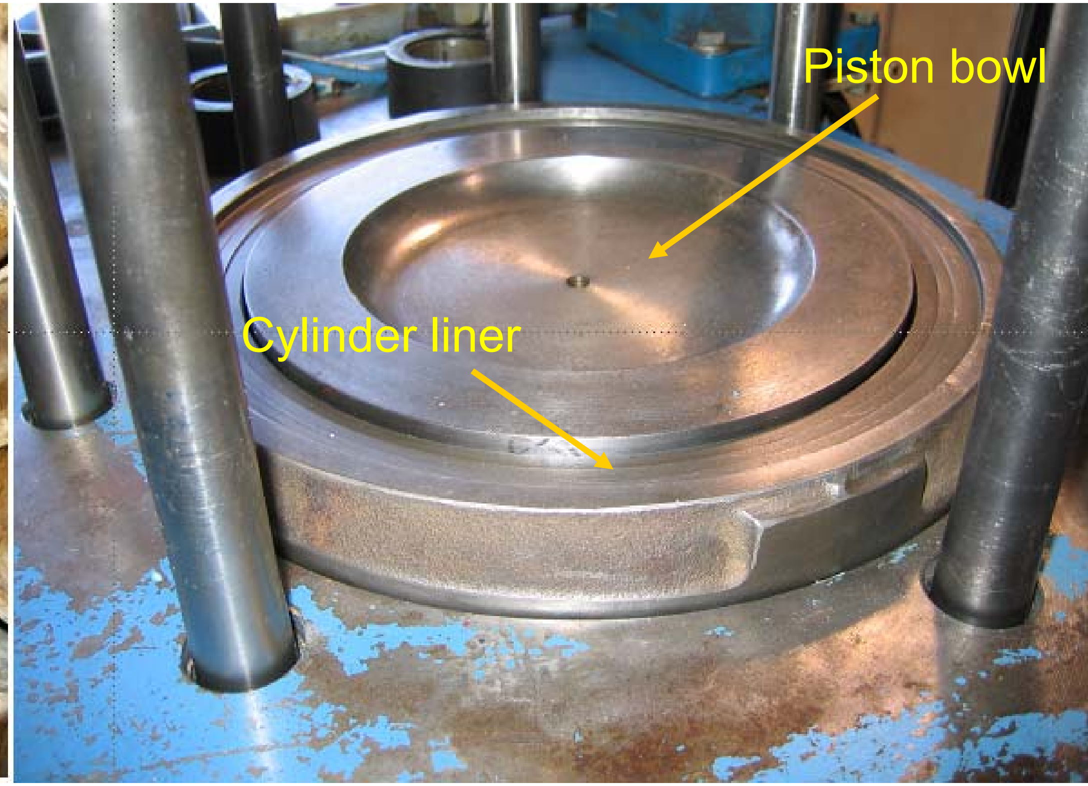
Free-space laser ignition tests

- A compact laser directly mounted on the cylinder head
- A sapphire lens in the cylinder head focused the laser to generate spark



Combustion Chamber





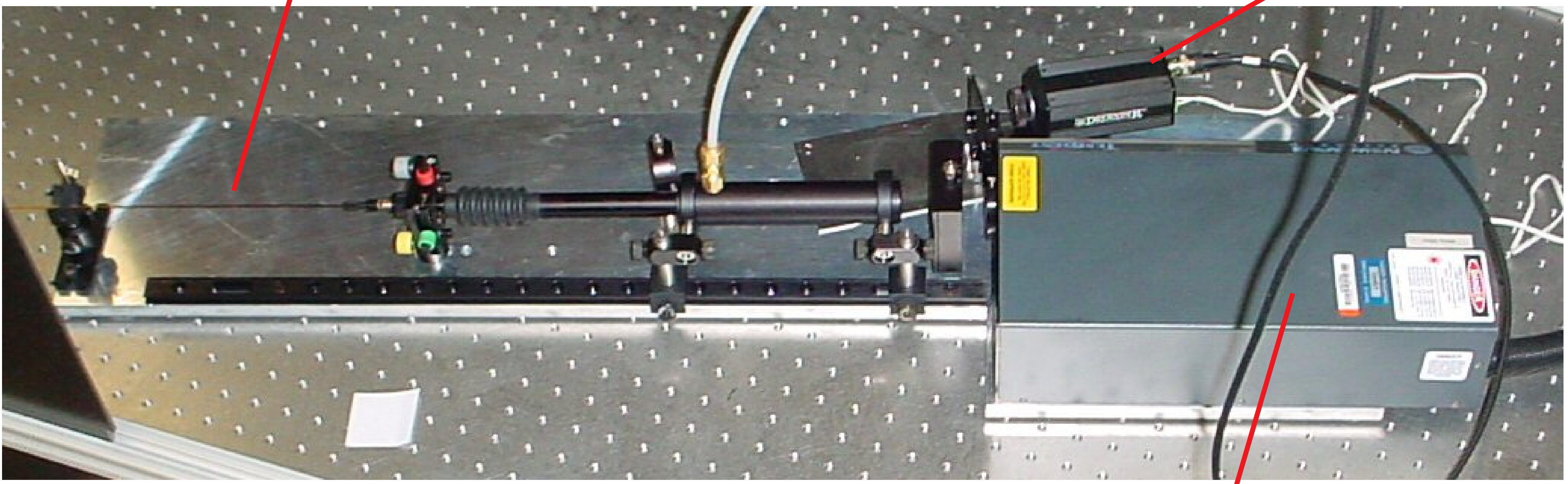
Spark position: 13 mm from lens face and 30 mm from piston at TDC

A Fiber coupled System was Prepared for on-engine Testing

700 μm core HGW for 532 nm

Dry nitrogen purge

CCD for alignment



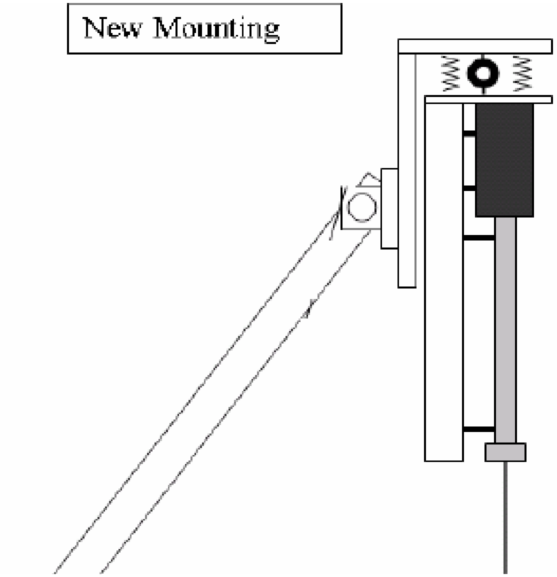
Compact laser

In lab environment the system operated for > 24 Hrs while moving the laser plug ± 6 mm in the transverse direction

Subsequent on-engine testing proved successful (06/10/05)

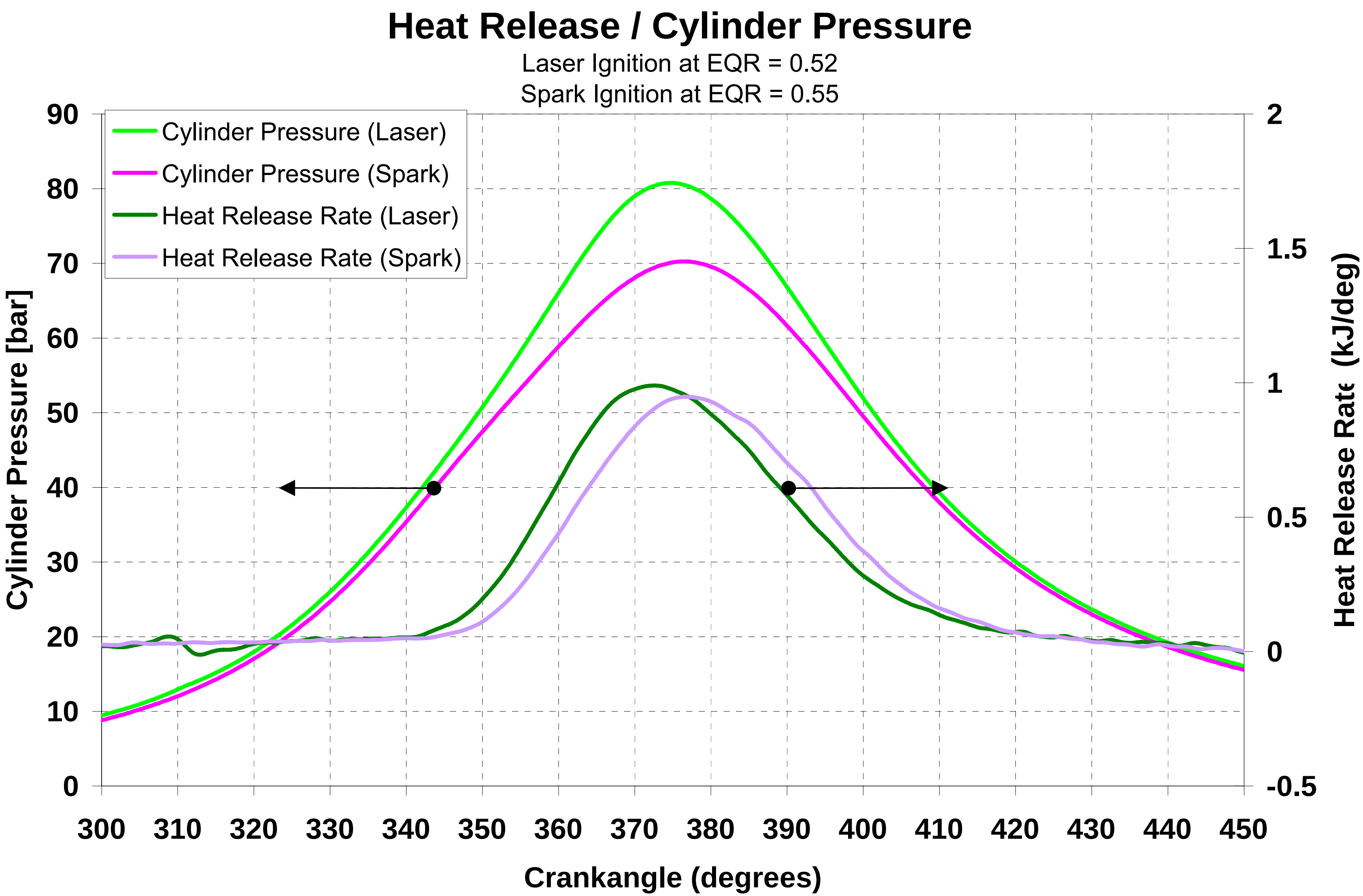
- **Ag/COP coated hollow core fiber for 532 nm**
- **28” long and 700μm ID**
- **15 degrees with vertical**
- **Dry Nitrogen purge**
- **Achieved 100% ignition probability at ϕ = 0.6 and 10 bar BMEP**

On a Parallel front ColoState Demonstrated Fiber Coupled Laser Ignition on Their 6-cyl Engine (6/08/05)

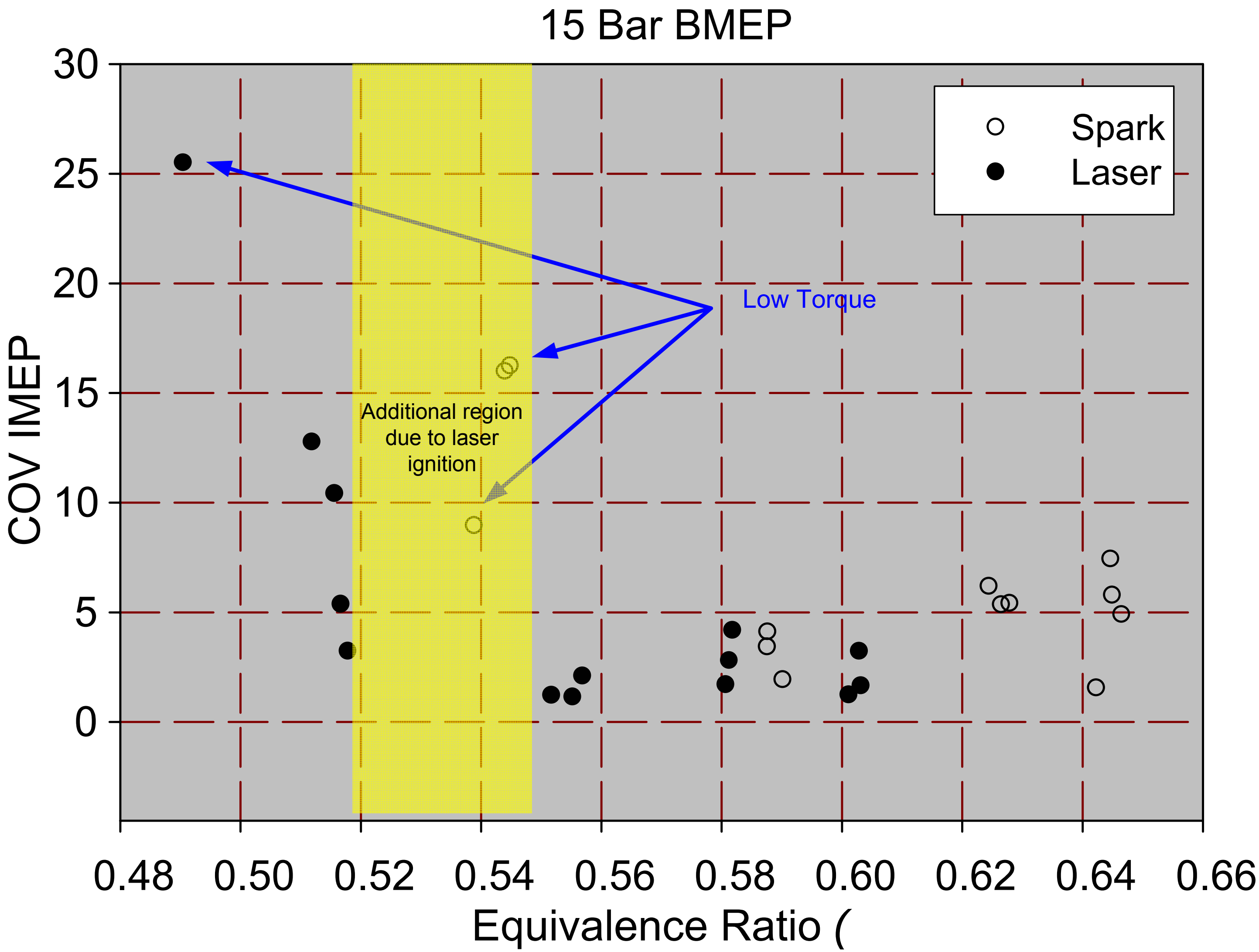


- 1 mm core Ag/COP hollow core fibers @ 1064 nm
- Vibration isolation for launch optics
- System under rough vacuum to avoid internal sparking
- Straight fiber to avoid beam degradation due to bending

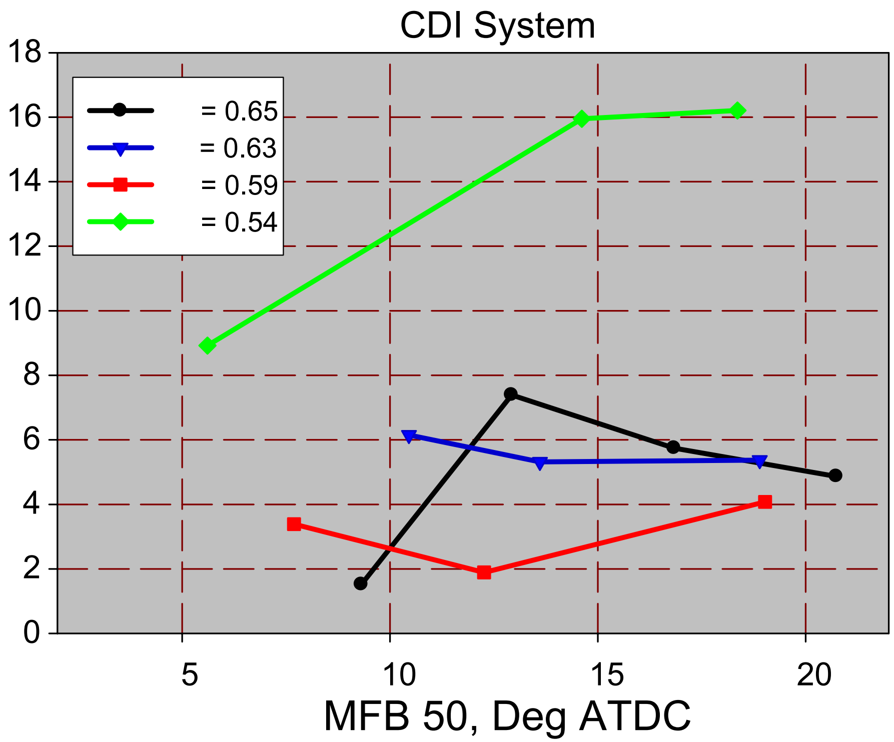
Laser Ignition Shows Faster Burn Rates

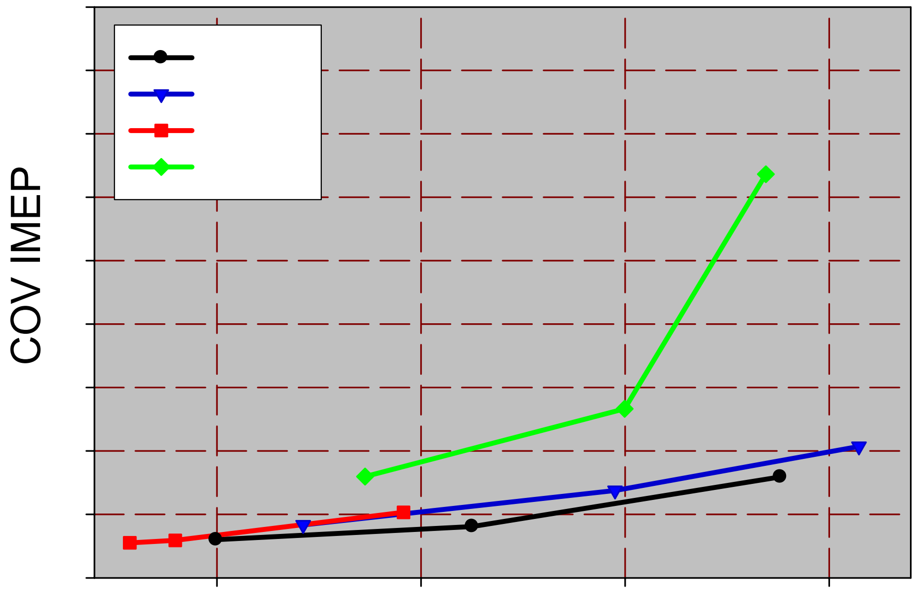


LI Extends Lean Ignition Limit

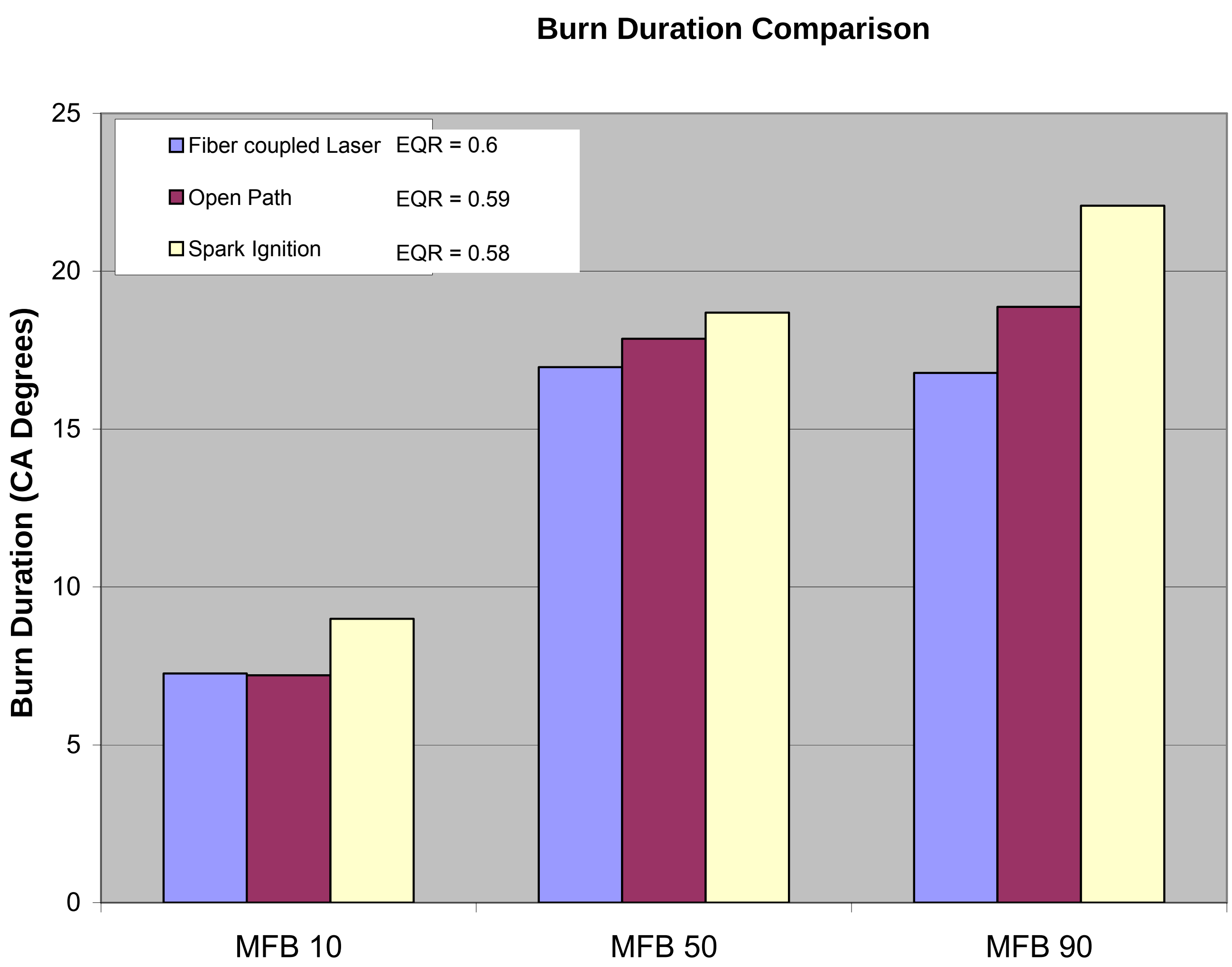


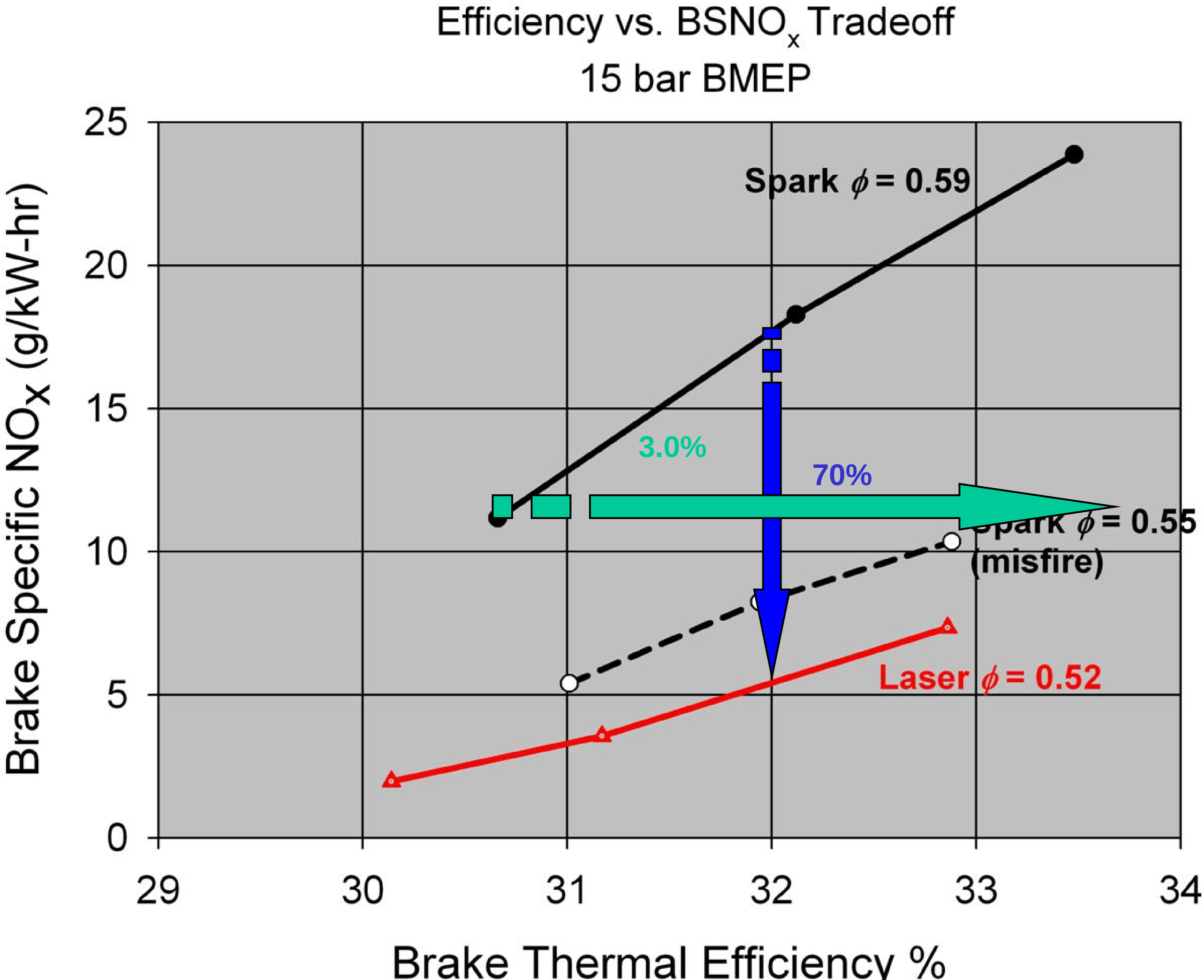
LI Shows Improved Combustion Stability





In the case of laser ignition, the burn rate is accelerated





Efficiency vs. BSNO$_x$ Tradeoff
15 bar BMEP
Spark ϕ = 0.59
3.0%
70%
Spark ϕ = 0.55
(misfire)
Laser ϕ = 0.52
Brake Specific NO$_x$ (g/kW-hr)
Brake Thermal Efficiency %
0
5
10
15
20
25
29
30
31
32
33
34

2.5 Integrate ALIS and Refine for Performance (On-going)

- Integrate previously developed ALIS components into a system for use with a 6-cylinder engine

2.6 Performance Evaluation of ALIS-ARICE System

- Tests on a large-bore, turbocharged, lean burn engine.
  - *ALIS installed on a large multi-cylinder engine*
  - *Engine manufacturer test cell OR Shell Oil rigs*

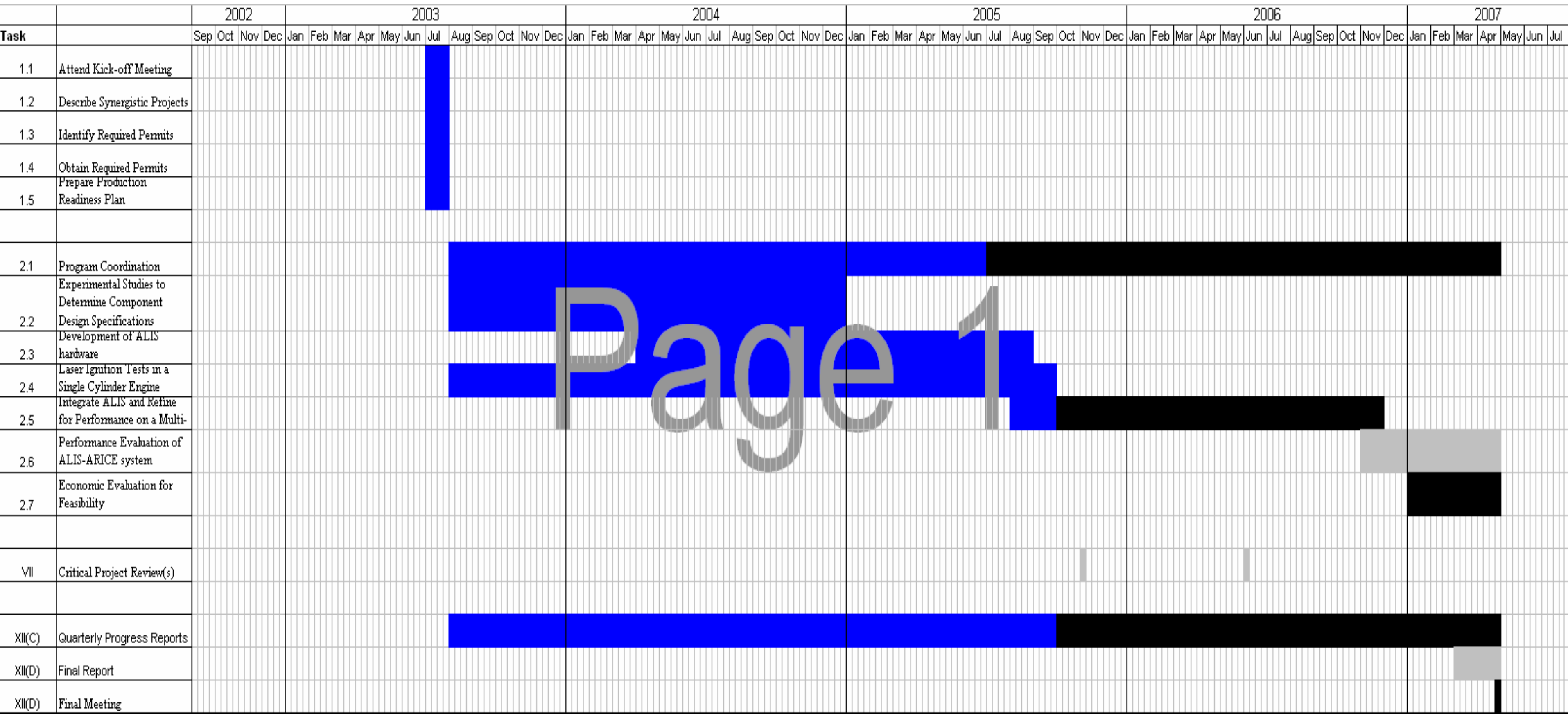
2.7 Economic Evaluation for Feasibility

- Evaluate the economic feasibility of ALIS Based on the performance benefits identified through Task 2.6.

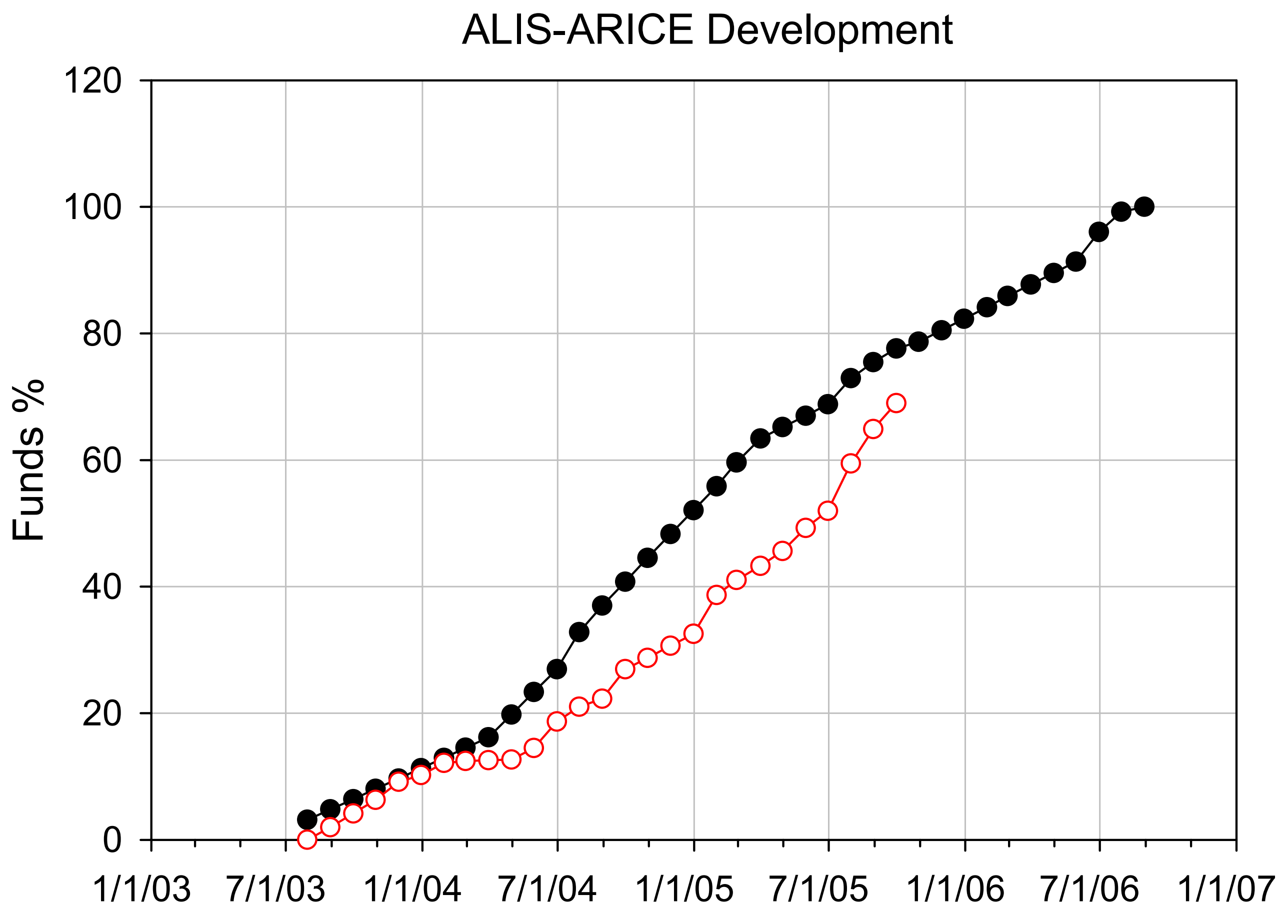
Schedule

Task	Task Name	Status
2.1	Program coordination	On-going
2.2	Experimental Studies to determine design specifications	√
2.3	Development of ALIS hardware	√?
2.4	Laser ignition tests in a single-cylinder engine	√?
2.5	Integrate ALIS for performance on a multi-cylinder engine	On-going?
2.6	Performance Evaluation of ALIS-ARICE system	
2.7	Economic Evaluation for feasibility	
	Final report	31-Dec-06

Gantt Chart (Updated till Sept. 05)



Financial Chart

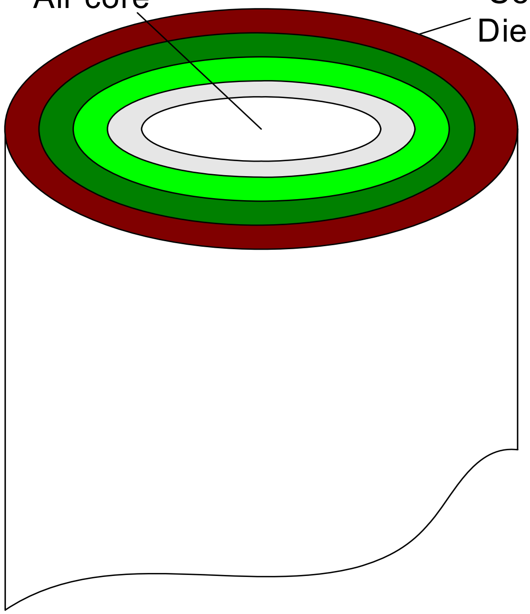


Beam Quality Degradation due to Fiber Bending is a Concern

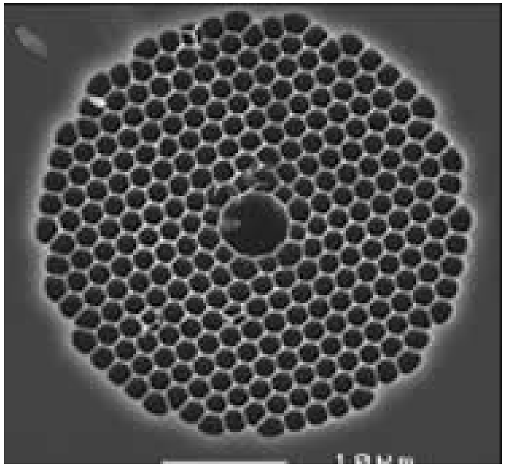
Bend insensitive fibers are required

Two Bend Insensitive Optical Fiber Technologies are Being Pursued

Multi-layer
Hollow Glass Waveguides



Photonic bandgap fibers



- **To accommodate such tests a no-cost extension to April 2007 was requested**

Summary

- Lean-burn engine technology is very attractive for the high engine efficiencies and low NO_x emissions. Considering future California emission regulations, further lean operation is desired which can only be achieved using advanced ignition systems such as Laser Ignition.

- An ALIS Consortium was formed with co-funding from USDOE to develop an Advanced Laser Ignition System (ALIS).

- Rapid Compression Machine (RCM) tests showed laser ignition to extend the lean ignition limit of natural gas all the way to the lean flammability limit ($\phi = 0.5$).

- Large-bore single-cylinder engine tests showed:
  - up to 70% reductions in NO_x emissions for a given efficiency, or
  - up to 3% points increase in Brake Thermal Efficiency for a given NO_x emission

- ALIS components: Laser Plug has been developed. Multiplexers were designed and are being developed and tested. The fiber optic delivery systems tested so far is bend sensitive. Efforts are continuing to obtain fiber optic delivery systems with the required performance.

Conclusions

- An ALIS consortium was formed in 2002 to develop the ALIS with funds from USDoE and CEC

Fundamental Studies

- Rapid Compression Machine tests showed that laser ignition has better ignition performance over conventional (CDI) ignition
  - LI extends the natural gas lean ignition limit all the way to the lean flammability limit ($\phi = 0.5$)
  - Shorter ignition delays and accelerated combustion occur with LI
- Trends observed for Minimum Required Energies using the RCM showed that a laser ignition system developed for $\phi = 0.5$ will perform under all other equivalence ratios (i.e., $0.5 \leq \phi \leq 1.0$)

Single Cylinder Engine Studies

- Large-bore single-cylinder engine tests showed:
  - Laser ignition has better combustion stability than CDI ignition
  - Laser ignition accelerates combustion leading to rapid heat release
  - For a given engine efficiency, Laser ignition can reduce NO_x up to 70%
  - For a given NO_x emission, Laser ignition can improve Brake Thermal Efficiency up to 3% points

Conclusions Contd.

Advanced Laser Ignition System (ALIS) Development

- A survey showed that Diode Pumped Solid State (DPSS) Laser technology is suitable for engine ignition application.

- A Multiplexing approach that distributes the output of a single laser to various engine-cylinders was identified to be suitable and the development of the related components was pursued:

  - Laser Plugs - Multiplexer - Fiber optic beam delivery

- Laser plugs of required performance were designed and manufactured.

- Suitable designs of multiplexers were developed. Performance evaluation of the prototypes is underway.

- While hollow glass wave guides were partly successful their performance is limited by their bend sensitivity. Currently pursuing efforts to get bend insensitive optical fibers.

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